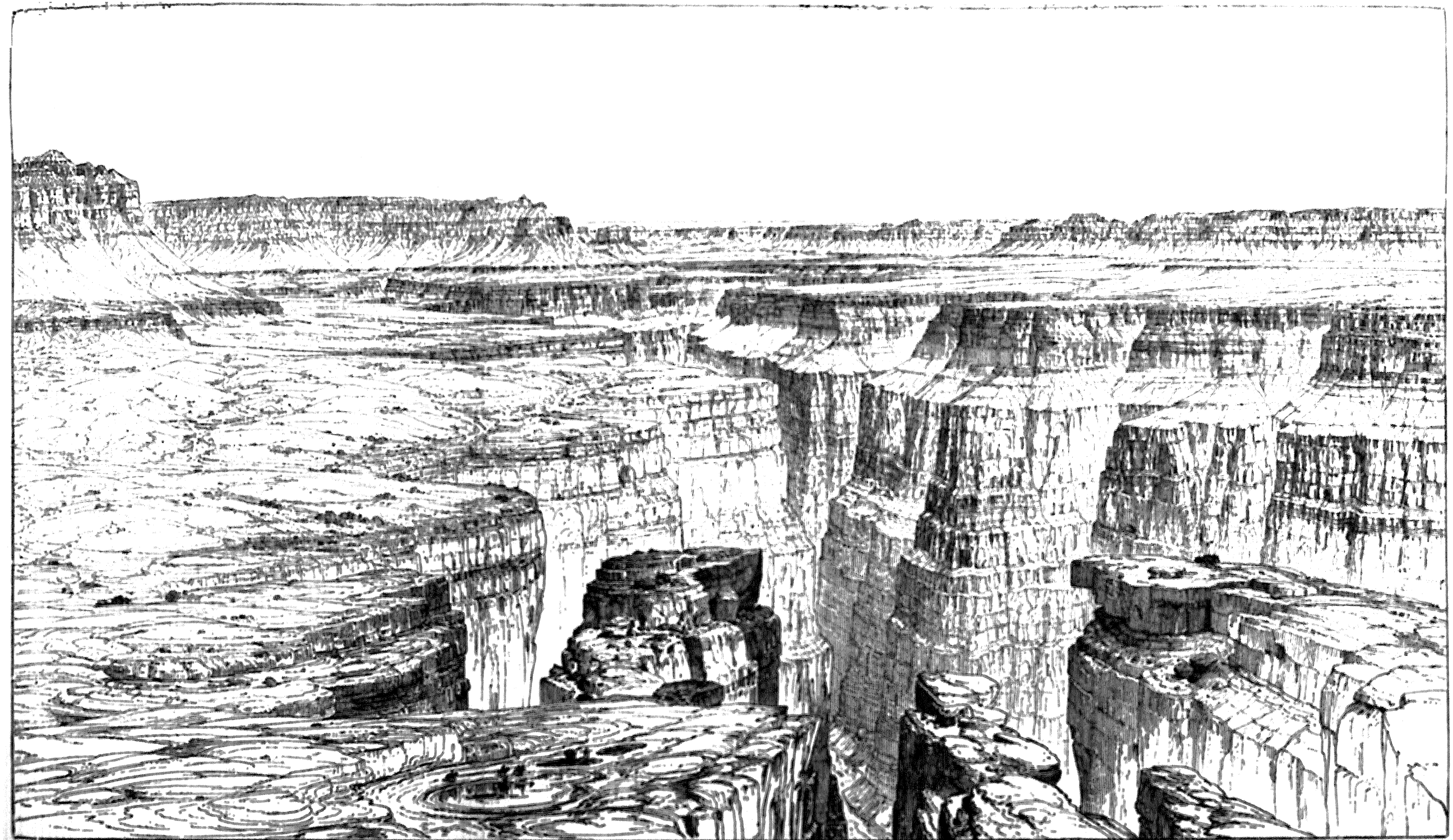
# TEXT-BOOK OF GEOLOGY



Frontispiece.

THE PLATEAU AND CAÑONS OF THE COLORADO.

# TEXT-BOOK OF GEOLOGY

BY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# PREFACE TO THE FOURTH EDITION.

In preparing the present Edition of this Text-book, I have endeavoured to bring every section of it abreast of the onward march of Geological Science. Some portions have been recast or rewritten; others have been largely augmented by the incorporation of the results of the latest researches, while between thirty and forty illustrations have been added. As the new material thus supplied amounts to 300 pages, the work has now been divided, for more convenient use, into two volumes; but to facilitate reference their pagination has been made continuous. So uninterrupted, however, is the progress of investigation, that since the sheets of most of the book were successively printed off, various valuable memoirs have appeared of which it has not been possible to make use.

As in previous Editions, copious references have been inserted to sources of more ample information in each branch of the science. A detailed Table of Contents for the whole work is placed at the beginning of the first volume, while the Index of Subjects at the end of the second volume has been made as full as the requirements of the student seemed to demand. These requirements have been further kept in view by the insertion of numerous cross-references, which it is hoped will enable the reader more easily to follow up any desired path through the various sections of geological enquiry.

I have to acknowledge with grateful thanks the valuable assistance given by Mr. H. Woods, F.G.S., of the Woodwardian Museum, Cambridge, in the revision of the Stratigraphical Geology, which forms Book VI. He has gone through the great labour of checking the synonymy of the genera and species of fossils and of bringing it up to the present stage of palæontological nomenclature.

# FROM THE PREFACE TO THE FIRST EDITION.

THE method of treatment adopted in this Text-book is one which, while conducting the class of Geology in the University of Edinburgh, I have found to afford the student a good grasp of the general principles of the science, and at the same time a familiarity with and interest in details of which he is enabled to see the bearing in the general system of knowledge. A portion of the volume appeared in the autumn of 1879 as the article "Geology" in the *Encyclopædia Britannica.* My leisure since that date has been chiefly devoted to expanding those sections of the treatise which could not be adequately developed in the pages of a general work of reference.

While the book will not, I hope, repel the general reader who cares to know somewhat in detail the facts and principles of one of the most fascinating branches of natural history, it is intended primarily for students, and is therefore adapted specially for their use. The digest given of each subject will be found to be accompanied by references to memoirs where a fuller statement may be sought. It has long been a charge against the geologists of Great Britain that, like their countrymen in general, they are apt to be somewhat insular in their conceptions, even in regard to their own branch of science. Of course, specialists who have devoted themselves to the investigation of certain geological formations or of a certain group of fossil animals, have made themselves familiar with what has been written upon their subject in other countries. But I am afraid there is still not a little truth in the charge, that the general body of geologists here is but vaguely acquainted with geological types and illustrations other than such as have been drawn from the area of the British Isles. More particularly is the accusation true in regard to American geology. Comparatively few of us have any adequate conception of the simplicity and grandeur of the examples by which the principles of the science have been enforced on the other side of the Atlantic.

Fully sensible of this natural tendency, I have tried to keep it in constant view as a danger to be avoided as far as the conditions of my task would allow. In a text-book designed for use in Britain, the illustrations must obviously be in the first place British. A truth can be enforced

much more vividly by an example culled from familiar ground than by one taken from a distance. But I have striven to widen the vision of the student by indicating to him that while the general principles of the science remain uniform, they receive sometimes a clearer, sometimes a somewhat different, light from the rocks of other countries than our own. If from these references he is induced to turn to the labours of our fellow-workers on the Continent, and to share my respect and admiration for them, a large part of my design will have been accomplished. If, further, he is led to study with interest the work of our brethren across the Atlantic, and to join in my hearty regard for it and for them, another important section of my task will have been fulfilled. And if in perusing these pages he should find in them any stimulus to explore nature for himself, to wander with the enthusiasm of a true geologist over the length and breadth of his own country, and, where opportunity offers, to extend his experience and widen his sympathies by exploring the rocks of other lands, the remaining and chief part of my aim would be attained.

The illustrations of Fossils in Book VI. have been chiefly drawn by Mr. George Sharman; a few by Mr. B. N. Peach, and one or two by Dr. R. H. Traquair, F.R.S., to all of whom my best thanks are due. The publishers having become possessed of the wood-blocks of Sir Henry de la Beche's 'Geological Observer,' I gladly made use of them as far as they could be employed in Books III. and IV. Sir Henry's sketches were always both clear and artistic, and I hope that students will not be sorry to see some of them revived. They are indicated by the letter (*B*). The engravings of the microscopic structure of rocks are from my own drawings, and I have also availed myself of materials from my sketch-books. The frontispiece is a reduction of a drawing by Mr. W. H. Holmes, whose pictures of the scenery in the Far West of the United States are by far the most remarkable examples yet attained of the union of artistic effectiveness with almost diagrammatic geological distinctness and accuracy. Captain Dutton, of the Geological Survey of the United States, furnished me with this drawing, and also requested Mr. Holmes to make for me the cañon-sections given in Book VII. To both of these kind friends I desire to acknowledge my indebtedness.

# CONTENTS.

## VOLUME I.



## BOOK I.

### COSMICAL ASPECTS OF GEOLOGY, 13.



## BOOK II.

### GEOGNOSY—AN INVESTIGATION OF THE MATERIALS OF THE EARTH'S SUBSTANCE.

#### PART I.—A GENERAL DESCRIPTION OF THE PARTS OF THE EARTH.



#### PART II.—AN ACCOUNT OF THE COMPOSITION OF THE EARTH'S CRUST—MINERALS AND ROCKS.

## BOOK III.

### Dynamical Geology, 260.

### Part I.—Hypogene Action—An Inquiry into the Geological Changes in Progress beneath the Surface of the Earth, 262.

# BOOK IV.

## Geotectonic (Structural) Geology, or the Architecture of the Earth's Crust.

## Part IV.—Curvature, 672.



## Part V.—Cleavage, 684.

## Part VI.—Dislocation, 687.



---

# VOLUME II.

## Part VII.—Eruptive (Igneous) Rocks as Part of the Structure of the Earth's Crust, 705.



## Part VIII.—Metamorphism, Local and Regional, 764.

## PART IV.—CAINOZOIC OR TERTIARY, 1219.



## PART V.—POST-TERTIARY OR QUATERNARY, 1300.

# BOOK VII.

## PHYSIOGRAPHICAL GEOLOGY.

# ABBREVIATIONS.

| | |
|---|---|
| *Abh.* | Abhandlungen. |
| Acad. Belg. | Académie Royale des Sciences, &c., de Belgique, Brussels. |
| Accad. Lincei | Reale Accademia dei Lincei, Rome. |
| ,, Napoli | Reale Accademia delle Scienze e Belle Lettere, Naples. |
| Akad. Bayer | Königliche Bayerische Akademie der Wissenschaften, Munich. |
| ,, Berlin | Kaiserliche Akademie der Wissenschaften zu Berlin. |
| ,, Stockholm | Kongliga Svenska Vetenskaps-Akademien, Stockholm. |
| ,, Wien | Kaiserliche Akademie der Wissenschaften, Vienna. |
| Amer. Acad. | American Academy of Arts and Sciences, Boston, Mass. |
| *Amer. Assoc.* | Proceedings of the American Association for the Advancement of Science. |
| *Amer. Geol.* | The American Geologist, Minneapolis. |
| *Amer. Inst. Min. Engin.* | Transactions of the American Institute of Mining Engineers, New York. |
| *Amer. Journ. Sci.* | The American Journal of Science, New Haven, Conn. |
| *Ann.* | Annalen, Annals, Annuaire, Annual. |
| *Ann. Chim.* | Annales de Chimie et de Physique, Paris. |
| *Ann. Mag. Nat. Hist.* | The Annals and Magazine of Natural History, London. |
| *Ann. Min.* | Annales des Mines, Paris. |
| *Ann. Phys. Chem.* | Annalen der Physik und Chemie (Poggendorff, Wiedemann), Leipzig. |
| *Ann. Ponts Chauss.* | Annales des Conducteurs des Ponts et Chaussées, Paris. |
| *Ann. Rep. U.S. G. S.* | Annual Report of the United States Geological Survey. |
| *Ann. Soc. Géol. Nord* | Annales de la Société Géologique du Nord, Lille. |
| *Arch. Neer.* | Archives Néerlandaises des Sciences Exactes et Naturelles, Haarlem. |
| *Arch. Sci. Phys. Nat.* | Archives des Sciences Physiques et Naturelles (Bibliothèque Universelle), Geneva. |
| *Assoc. Franç.* | Compte Rendu de l'Association Française pour l'Avancement des Sciences, Paris. |
| *Astr. Nach.* | Astronomische Nachrichten, Kiel. |
| *Att.* | Atti. |
| *B., Bull.* | Bulletin. |
| *B. S. G. F.* | Bulletin de la Société Géologique de France, Paris. |
| *B. U.S. G. S.* | Bulletin of the United States Geological Survey, Washington. |
| Badisch. Landes. | Grossherzogliche Badische Geologische Landesanstalt. |
| *Bih.* | Bihang. |
| *Bol.* | Bollettino. |
| *Brit. Assoc.* | Reports of the British Association for the Advancement of Science, London. |
| *Camb. Phil. Trans.* | Transactions of the Cambridge Philosophical Society, Cambridge. |
| *Carte Géol. France* | Carte Géologique Detailée de la France, Paris. [Maps, Bulletin and Mémoires.] |

| | |
|---|---|
| *Chem. News* | The Chemical News and Journal of Physical Science, London. |
| *Com.* | Comitato, Comité, Commission. |
| *Com. Direc. Trabal. Geol.* | Direcção dos Trabalhos Geologicos de Portugal, Lisbon. |
| *Com. Géol. Russ.* | Comité Géologique de la Russie, St. Pétersbourg. [Maps, Memoirs, Bulletins.] |
| *Compt. rend.* | Comptes rendus de l'Académie des Sciences, Paris. |
| *Congr. Geol. Internat.* | Comptes Rendus du Congrès Géologique International. |
| *Denk.* | Denkschriften. |
| *Edin. Phil. Journ.* | The Edinburgh New Philosophical Journal, Edinburgh [1826-1864]. |
| *Explor. 40th Parall.* | Report of the Geological Exploration of the Fortieth Parallel, Washington. |
| *Forhand. Vid.-Selks.* | Forhandlinger i Videnskabs-Selskabet i Christiania. |
| *Geogr. Journ.* | Journal of the Royal Geographical Society, London [1832-1892], and The Geographical Journal [from 1893]. |
| *Geol. Assoc.* | Proceedings of the Geologists' Association, London. |
| *Geol. Fören. Stockh.* | Geologiska Föreningens i Stockholm Förhandlingar, Stockholm. |
| *Geol. Mag.* | The Geological Magazine, London. |
| Geol. Reichs. | K. K. Geologische Reichsanstalt, Vienna. [Maps, Verhandlungen, Jahrbuch, and Abhandlungen.] |
| Geol. Soc. | Geological Society of London. |
| Geol. Soc. Am. | Geological Society of America. |
| *Geol. Trans.* | Transactions of the Geological Society of London. |
| Ges. | Gesellschaft. |
| Inst. Civ. Engin. | Institute of Civil Engineers, London. |
| *J., Journ.* | Journal. |
| *Jahrb.* | Jahrbuch. |
| *Journ. Coll. Sci. Univ. Japan* | Journal of the College of Science, Imperial University of Tōkyō, Japan. |
| *Journ. Geol.* | Journal of Geology, Chicago [from 1893]. |
| *K. D. Vid. Selsk. Forh.* | Det Konglige Danske Videnskabernes Selskabs Forhandlinger, Copenhagen. |
| *Kart. Sachsen* | Erläuterungen zur Geologischen Specialkarte des Königreichs Sachsen, Leipzig. |
| *Mem.* | Memoirs, Mémoires. |
| *Mem. Geol. Surv.* | Memoirs of the Geological Survey of Great Britain. |
| *Micr. Journ.* | Quarterly Journal of Microscopical Science, London. |
| *Min. Mag.* | Mineralogical Magazine, London. |
| *Min. Proc. Inst. Civ. Engineers* | Minutes and Proceedings of the Institute of Civil Engineers, London. |
| *Mitth.* | Mittheilungen. |
| *Mon.* | Monograph. |
| Mus. | Musée, Museum. |
| Mus. Comp. Zool. | Museum of Comparative Zoology, Harvard, Massachusetts. |
| *Mus. Teyler* | Musée Teyler, Archives, Haarlem. |
| *N. Jahrb., Neues Jahrb.* | Neues Jahrbuch für Mineralogie, Geologie und Paläontologie, Stuttgart. |
| *Nat. Geog. Mag.* | National Geographic Magazine, Washington. |
| Nat. Sci. | Natural Sciences. |
| Norg. Geol. Undersög. | Norges Geologiske Undersögelse [Aarbog, &c.], Christiania. |
| N. Y. Acad. Sci. | New York Academy of Sciences. |
| *Nyt Mag.* | Nyt Magazin for Naturvidenskaberne. Christiania. |

| | |
|---|---|
| *Peterm. Mitth.* | Petermann's Mittheilungen ; Justus Perthes, Gotha. |
| *Phil. Mag.* | The London, Edinburgh, and Dublin Philosophical Magazine, London. |
| *Phil. Trans.* | Philosophical Transactions of the Royal Society of London. |
| *Pogg. Ann.* | Poggendorff's Annalen, *see above* under *Ann. Phys. Chem.* |
| *Pop. Sci. Monthly* | Popular Science Monthly, New York. |
| *Pop. Sci. Rev.* | The Popular Science Review, London. |
| Preuss. Landes. | Konigliche Preussische Geologische Landesanstalt [Specialkarte, Jahrbuch, Erlauterungen, Abhandlungen], Berlin. |
| *Proc.* | Proceedings. |
| *Q. J. G. S.* | Quarterly Journal of the Geological Society of London. |
| R. S., Roy. Soc. | Royal Society. |
| *Rend.* | Rendiconti. |
| *Rep.* | Report. |
| *Rev. Sci.* | Revue Scientifique, Paris. |
| Sci. | Science, Scientific. |
| Seism., Sism. | Seismological, Sismologica. |
| *Sitzb.* | Sitzungsberichte. |
| *Smithson. Contrib.* | Smithsonian Contributions to Knowledge, Washington. |
| Smithson. Inst. | Smithsonian Institution, Washington. |
| *Smithson. Misc. Coll.* | Smithsonian Miscellaneous Collections, Washington. |
| Soc. | Society, Société, Società. |
| Svensk. Vet. Akad. | *See above* under Akad. |
| Sverig. Geol. Undersokn. | Sveriges Geologiska Undersokning [Maps, Afhandlingar], Stockholm. |
| *Trans.* | Transactions. |
| *Tscherm. Mitth.* | Tschermak's Mineralogische und Petrographische Mittheilungen, Vienna. |
| U.S. G. S. | United States Geological Survey. |
| U.S. Nat. Mus. | United States National Museum. |
| Ver. | Verein. |
| *Verh.* | Verhandlungen. |
| Vid. Med. Nat. Foren. | Videnskabelige Meddelelser fra den Naturhistoriske Forening i Kjöbenhaven, Copenhagen. |
| Wiedem. Ann. | *See above* under *Ann. Phys. Chem.* |
| Wiss. | Wissenschaften. |
| *Z.*, *Zeitsch.* | Zeitschrift. |
| *Z. D. G. G.* | Zeitschrift der Deutschen Geologischen Gesellschaft, Berlin. |
| *Zeitsch. Kryst.* | Zeitschrift fur Krystallographie und Mineralogie (Groth), Leipzig. |

# INTRODUCTION.

GEOLOGY is the science which investigates the history of the Earth. Its object is to trace the progress of our planet from the earliest beginnings of its separate existence, through its various stages of growth, down to the present condition of things. Unravelling the complicated processes by which each continent and country has been built up, it traces out the origin of their materials and the successive stages by which these materials have been brought into their present form and position. It thus unfolds a vast series of geographical revolutions that have affected both land and sea all over the face of the globe.

Nor does this science confine itself merely to changes in the inorganic world. Geology shows that the present races of plants and animals are the descendants of other and very different races that once peopled the earth. It teaches that there has been a progress of the inhabitants, as well as one of the globe on which they have dwelt; that each successive period in the earth's history, since the introduction of living things, has been marked by characteristic types of the animal and vegetable kingdoms; and that, how imperfectly soever they may have been preserved or may be deciphered, materials exist for a history of life upon the planet. The geographical distribution of existing faunas and floras is often made clear and intelligible by geological evidence; and in a similar way, light is thrown upon some of the remoter phases in the history of man himself.

A subject so comprehensive as this must require a wide and varied basis of evidence. One of the characteristics of geology is to gather evidence from sources which, at first sight, seem far removed from its scope, and to seek aid from almost every other leading branch of science. Thus, in dealing with the earliest conditions of the planet, the geologist must fully avail himself of the labours of the astronomer. Whatever is ascertainable by telescope, spectroscope, or chemical analysis, regarding the constitution of other heavenly bodies, has a geological bearing. The experiments of the physicist, undertaken to determine conditions of matter and of energy, may sometimes be taken as the starting-point of geological investigation. The work of the chemical laboratory forms the foundation of a vast and increasing mass of geological inquiry. To the

botanist, the zoologist, even to the unscientific, if observant, traveller by land or sea, the geologist turns for information and assistance.

But while thus culling freely from the dominions of other sciences, geology claims, as its peculiar territory, the rocky framework of the globe. In the materials composing that framework, their composition and arrangement, the processes of their formation, the changes which they have individually undergone, and the grand terrestrial revolutions to which they bear witness, lie the main data of geological history. It is the task of the geologist to group these elements in such a way that they may be made to yield up their evidence as to the march of events in the evolution of the planet. He finds that they have in large measure arranged themselves in chronological sequence,—the oldest lying at the bottom and the newest at the top. Relics of an ancient sea-floor are overlain with traces of a vanished land-surface, these are in turn covered by the deposits of a former lake, above which once more appear proofs of the return of the sea. Among these rocky records, too, lie the lavas and ashes of long-extinct volcanoes. The ripple left upon a sandy beach, the cracks formed by the sun's heat upon the muddy bottom of a dried-up pool, the very imprint of the drops of a passing rain-shower, have all been accurately preserved, and often bear witness to geographical conditions widely different from those that exist where such markings are now found.

But it is mainly by the remains of plants and animals imbedded in the rocks that the geologist is guided in unravelling the chronological succession of geological changes. He has found that a certain order of appearance characterises these organic remains; that each successive group of rocks is marked by its own special types of life; that these types can be recognised, and the rocks in which they occur can be correlated, even in distant countries, where no other means of comparison are available. At one moment, he has to deal with the bones of some large mammal scattered through a deposit of superficial gravel; at another time, with the minute foraminifers and ostracods of an upraised sea-bottom. Corals and crinoids, crowded and crushed into a massive limestone on the spot where they lived and died, ferns and terrestrial plants matted together into a bed of coal where they originally grew, the scattered shells of a submarine sand-bank, the snails and lizards that left their mouldering remains within a hollow tree, the insects that have been imprisoned within the exuding resin of old forests, the footprints of birds and quadrupeds, or the trails of worms left upon former shores—these, and innumerable other pieces of evidence, enable the geologist to realise in some measure what the vegetable and animal life of successive periods has been, and what geographical changes the site of every land has undergone.

It is evident that to deal successfully with these varied materials, a considerable acquaintance with different branches of science is desirable. The fuller and more accurate the knowledge which the geologist has of kindred branches of inquiry, the more interesting and fruitful will be his own researches. From its very nature, geology demands on the part of

its votaries wide sympathy with investigation in almost every branch of natural science. Especially necessary is a tolerably large acquaintance with the processes now at work in changing the surface of the earth, and of at least those forms of plant and animal life whose remains are apt to be preserved in geological deposits, or which, in their structure and habitat, enable us to realise what their forerunners were.

It has often been insisted upon that the Present is the key to the Past; and in a wide sense this assertion is eminently true. Only in proportion as we understand the present, where everything is open on all sides to the fullest investigation, can we expect to decipher the past, where so much is obscure, imperfectly preserved, or not preserved at all. A study of the existing economy of nature ought evidently to be the foundation of the geologist's training.

While, however, the present condition of things is thus employed, we must obviously be on our guard against the danger of unconsciously assuming that the phase of nature's operations which we now witness has been the same in all past time; that geological changes have taken place, in former ages, in the manner and on the scale which we behold to-day, and that at the present time all the great geological processes, which have produced changes in past eras of the earth's history, are still existent and active. Of course, we may assume this uniformity of action, and use the assumption as a working hypothesis. But it ought not to be allowed a firmer footing, nor on any account be suffered to blind us to the obvious truth that the few centuries, wherein man has been observing nature, form much too brief an interval by which to measure the intensity of geological action in all past time. For aught we can tell, the present is an era of quietude and slow change, compared with some of the eras that have preceded it. Nor can we be sure that when we have explored every geological process now in progress, we have exhausted all the causes of change which, even in comparatively recent times, have been at work.

In dealing with the Geological Record, as the accessible solid part of the globe is called, we cannot too vividly realise that, at the best, it forms but an imperfect chronicle. Geological history cannot be compiled from a full and continuous series of documents. Owing to the very nature of its origin, the record is necessarily from the first fragmentary, and it has been further mutilated and obscured by the revolutions of successive ages. Even where the chronicle of events is continuous, it is of very unequal value in different places. In one case, for example, it may present us with an unbroken succession of deposits, many thousands of feet in thickness, from which, however, only a few meagre facts as to geological history can be gleaned. In another instance, it brings before us, within the compass of a few yards, the evidence of a most varied and complicated series of changes in physical geography, as well as an abundant and interesting suite of organic remains. These and other characteristics of the geological record will become more apparent and intelligible to the student as he proceeds in the study of the science.

In the present volume the subject will be distributed under the following leading divisions.

1. *The Cosmical Aspects of Geology.*—It is desirable to realise some of the more important relations of the earth to the other members of the solar system, of which it forms a part, seeing that geological phenomena are largely the result of these relations. The form and motions of the planet may be briefly touched upon, and attention should be directed to the way in which these planetary movements influence geological change. The light cast upon the early history of the earth by researches into the composition of the sun and stars deserves notice here.

2. *Geognosy—An Inquiry into the Materials of the Earth's Substance.*—This division describes the constituent parts of the earth, its envelopes of air and water, its solid crust, and the probable condition of its interior. Especially, it directs attention to the more important minerals of the crust, and the chief rocks of which that crust is built up. In this way, it lays a foundation of knowledge regarding the nature of the materials constituting the mass of the globe, whence we may next proceed to investigate the processes by which these materials are produced and altered.

3. *Dynamical Geology* embraces an investigation of the operations which lead to the formation, alteration, and disturbance of rocks, and calls in the aid of physical and chemical experiment in elucidation of these operations. It considers the nature and operation of the processes that have determined the distribution of sea and land, and have moulded the forms of the terrestrial ridges and depressions. It further investigates the geological changes which are in progress over the surface of the land and floor of the sea, whether these are due to subterranean disturbance, or to the effect of operations above ground. Such an inquiry necessitates a careful study of the existing economy of nature, and forms a fitting introduction to the investigation of the geological changes of former periods. This and the previous section, including most of what is embraced under Physical Geography and Petrogeny or Geogeny, will here be discussed more in detail than is usual in geological treatises.

4. *Geotectonic, or Structural Geology—the Architecture of the Earth.*—This section of the investigation, applying the results arrived at in the previous division, discusses the actual arrangement of the various materials composing the crust of the earth. It proves that some have been formed in beds or strata, whether by the deposit of sediment on the floor of seas and lakes, or by the slow aggregation of organic forms; that others have been poured out from subterranean sources in sheets of molten rock, or in showers of loose dust, which have been built up into mountains and plateaux. It further shows that rocks originally laid down in almost horizontal beds have subsequently been crumpled, contorted, dislocated, invaded by igneous masses from below, and rendered sometimes crystalline. It teaches, too, that wherever exposed above sea-level, they have been incessantly worn down, and have often been depressed, so that older lie buried beneath later accumulations.

5. *Palæontological Geology.*—This branch of the subject deals with the organic forms which are found preserved in the rocks of the crust of the earth. It includes such questions as the manner in which the remains of plants and animals are entombed in sedimentary accumulations, the

relations between extinct and living types, the laws which appear to have governed the distribution of life in time and in space, the nature and use of the evidence from organic remains regarding former conditions of physical geography, and the relative importance of different genera of animals and plants in geological inquiry.

6. *Stratigraphical Geology.*—This section might be called Geological History, or Historical Geology. It works out the chronological succession of the great formations of the earth's crust, and endeavours to trace the sequence of events of which they contain the record. More particularly, it determines the order of succession of the various plants and animals which in past time have peopled the earth, and thus, by ascertaining what has been the grand march of life upon the planet, seeks to unravel the story of the earth as made known by the rocks of the crust. Further, by comparing the sequence of rocks in one country with that of those in another, it furnishes materials for enabling us to picture the successive stages in the geographical evolution of the various portions of the earth's surface.

7. *Physiographical Geology*, starting from the basis of fact laid down by stratigraphical geology regarding former geographical changes, embraces an inquiry into the history of the present features of the earth's surface—continental ridges and ocean basins, plains, valleys, and mountains. It investigates the structure of mountains and valleys, compares the mountains of different countries, and ascertains the relative geological dates of their upheaval. It explains the causes on which local differences of scenery depend, and shows under what very different circumstances, and at what widely separated intervals, the varied contours, even of a single country, have been produced.

In the present text-book references are given in each section of the subject to fuller sources of information to which the student may profitably turn. But it may be useful to him to have here a preliminary statement regarding general works of reference, some of which he might with advantage add to his library.

## WORKS OF REFERENCE, ETC.

History of Geological Science.—When he has made some general acquaintance with the nature and scope of geology, the learner will derive great benefit from a course of historical reading, which will enable him to trace the development of ideas and the gradual establishment of recognised principles upon an ever-widening basis of ascertained fact. The history of a science is best told in the lives and works of those who have been the chief workers in it. In the records of scientific achievement there are few more interesting chapters than those which trace the birth and growth of geology. One who makes himself familiar with these chapters will find that they enlarge his conceptions of the meaning and bearings of geological theory, and give a keener human interest to many of the inquiries which he has to pursue. It will eventually be found most satisfactory to turn to the original sources of information; but as these are scattered through different languages and are not always easily accessible, the student may at first with advantage make use of such digests of the history as may come into his hands. The first four chapters of Lyell's 'Principles of Geology' have long been the chief source

of information to English-speaking readers regarding the history of the progress of the science. Excellent as they are, they need amplification, especially for the period after the middle of the eighteenth century. Whewell's 'History of the Inductive Sciences' may also be usefully consulted. I have tried to supply some further details in my 'Founders of Geology,' which deals more particularly with the progress made between 1750 and 1820. In French, the works of D'Archiac are valuable; his 'Histoire des Progrès de la Géologie,' in eight volumes, brings down the record, especially of French workers, from 1834 to 1850, while his 'Cours de Paléontologie Stratigraphique' (1862) and his 'Géologie et Paléontologie' (1866) may be consulted. In German, Keferstein's 'Geschichte und Literatur der Geognosie' gives a convenient summary down to the year 1840. More valuable is the excellent digest by Professor Zittel in his 'Geschichte der Geologie und Paläontologie bis Ende des 19. Jahrhunderts' (1899). From these different treatises the student will be able to select such historical questions as he may wish to pursue, and the various authors through whose writings he may be able best to trace the progress of research.

Reference may be made here to the 'Catalogue des Bibliographies Géologiques,' by M. Emm. de Margerie, published under the auspices of the International Geological Congress, Paris, 1896, pp. xx, 733—a storehouse of directions for sources of information in all departments of geology, and for all parts of the world.

Guides to Methods of Geological Investigation.—Various hand-books have been published in this country and elsewhere as aids in the prosecution of geological investigation in the field and in the laboratory. The following list comprises a number which may be found of service:—

Ami Boué, 'Guide du Géologue Voyageur.' 2 vols. 1835-36.

Baron F. von Richthofen, 'Führer für Forschungsreisende.' Berlin, 1886.

Keilhack, 'Lehrbuch der praktischen Geologie—Arbeiten und Untersuchungsmethoden auf dem Gebiete der Geologie, Mineralogie und Paläontologie.' Stuttgart, 1896.

W. H. Penning, 'A Text-book of Field Geology,' with section on Palæontology by A. J. Jukes-Browne. London: Baillière and Co. 2nd edition. 1879.

A. Geikie, 'Outlines of Field Geology.' London: Macmillan and Co. 5th edition. 1900.

'Manual of Scientific Enquiry.' Published for the Admiralty. 5th edition. 1886.

G. A. T. Cole, 'Aids in Practical Geology.' London: Griffin and Co. 3rd edition. 1898.

H. Rosenbusch, 'Mikroskopische Physiographie der Mineralien und Gesteine. 2 vols. 3rd edition. 1896. Also the English version, 'Microscopical Physiography of Rock-forming Minerals,' by J. P. Iddings. 3rd edition. 1893. Further works of reference in Petrography will be found enumerated in Book II, Part II. Sect. iii. § iv.

L. de Launay, 'Géologie Pratique.' 1901.

General Treatises or Text-books of Geology.—Out of the vast number of class-books, hand-books, and other summaries of the elements, principles, and chief results of geological investigation, it is only possible to find room here for the mention of a few of the more important, and especially of the more recent, works and editions.

A. De Lapparent, 'Traité de Géologie.' Paris. 4th edition. 1900; in three volumes containing 1912 pages. This is the standard treatise in French.

H. Credner, 'Elemente der Geologie.' 8th edition. 1897.

E. Suess, 'Antlitz der Erde.' 3 vols. French trans. by E. de Margerie and others, with title, 'La Face de la Terre.' Paris, vol. i. 1897; vol. ii. 1900.

E. Kayser, 'Text-book of Comparative Geology.' Trans. P. Lake. London, 1893.

A. Supan, 'Grundzüge der physischen Erdkunde.' 2nd enlarged edition. Leipzig, 1896. An excellent digest of physical geography and geology.

S. Gunther, 'Handbuch der Geophysik.' 2 vols. Stuttgart, 1897-1900. A remarkably voluminous digest of the whole vast subject, with full references to original authorities.

A. Penck, 'Morphologie der Erdoberfläche.' 2 vols. Stuttgart, 1894.

F. Toula, 'Lehrbuch der Geologie.' Vienna, 1900.

K. Fritsch, 'Allgemeine Geologie.' Stuttgart, 1888.

A. Stoppani, 'Corso di Geologia.' 3 vols. Milan, 1871-73.

J. D. Dana, 'Manual of Geology.' 4th edition. New York, 1895. Valuable for its information regarding American geology.

J. Le Conte, 'Elements of Geology.' New York, 1889.

W. B. Scott, 'An Introduction to Geology.' New York, 1897.

De la Noë and E. de Margerie, 'Les Formes du Terrain.' Paris, 1888.

K. A. von Zittel, 'Handbuch der Palaeontologie.' 5 vols. French trans. by Barrois. 'Grundzüge der Palaeontologie.' Trans. into English by C. R. Eastman, with great modifications, and published as a 'Text-book of Palæontology,' vol. i. 1900; vol. ii. 1902.

A. Smith Woodward, 'Outlines of Vertebrate Palæontology for Students of Zoology,' pp. xxiv. 470. Cambridge, 1898.

D. H. Scott, 'Studies in Fossil Botany,' pp. xiii, 553. London, 1900.

A. C. Seward, 'Fossil Plants:—for Students of Botany and Geology.' Cambridge, vol. i. (1898).

Zeiller, 'Elements de Paléobotanique.' Paris, 1900, pp. 421. Other works are cited at the beginning of Book V.

Works on the applications of Geology:—

J. V. Elsden, 'Applied Geology.' In two parts. London, 1898-99.

G. P. Merrill, 'Stones for Building and Decoration.' 2nd edition. New York: Wiley; London: Chapman and Hall. 'The Physical, Chemical, and Economic Properties of Building Stones.' Maryland Geol. Survey. Special publ. vol. ii. part ii. Baltimore, 1898.

S. M. Burnham, 'History and Uses of Limestones and Marbles.' Boston: Cassino, 1883.

E. R. Buckley, "On the Building and Ornamental Stones of Wisconsin," *Wisconsin Geol. Surv. Bulletin*, No. v. Madison, Wis., 1898. This writer contributes a useful paper on "The Properties of Building Stones and Methods of determining their Value," *Journal of Geology*, Chicago, vol. viii. 1900, pp. 160, 333, 526, and supplies there a copious list of references to the subject. See also a paper by A. A. Julien in *Jour. Franklin Inst. Pennsylvania*, cxlvii. (1899), pp. 257, 378.

O. Herman, 'Steinbruch-Industrie und Steinbruch-Geologie,' pp. 428. Berlin, 1899.

H. Gruner, 'Landwirtschaft und Geologie.' 1879.

H. E. Stockbridge, 'Rocks and Soils.' 1885.

R. Warington, 'Lectures on some of the Physical Properties of Soil,' pp. xv, 231. Oxford, 1900.

H. B. Woodward, "Soils and Subsoils from a Sanitary Point of View," *Mem. Geol. Surv.* 1897, pp. vi, 58.

W. Whitaker, "Geology and Sanitary Science," *Jour. Sanitary Inst.*, vol. xviii. (1897), pp. 304-316.

W. H. Penning, 'Engineering Geology.' London, 1880.

W. Galloway, 'A Course of Lectures on Mining.' Cardiff. Published by South Wales Institute of Engineers. 1900.

W. Smyth, 'A Rudimentary Treatise on Coal and Coal-mining.' 8th edition, revised and extended by T. Forster Brown, pp. vi, 346. London, 1900.

J. A. Phillips and H. Louis, 'Ore Deposits.' 2nd edition, 1896.

C. le Neve Foster, 'A Text-book of Ore- and Stone-mining.' 4th edition. London, 1902.

F. A. Fuhrer, 'Salzbergen und Salinenkunde,' p. 1124. Brunswick, 1900.

Geological Maps.—It is impossible to follow intelligently the descriptions of the distribution of the rocks and the geological structure of a country without recourse to the best geological maps that are available. For the broader questions of geology and physical geography the maps of Berghaus and those of the Physical Atlas now in course of preparation by Bartholomew of Edinburgh will be found of value. For the geology of particular continents and countries the following list contains the more important and accessible maps :—

EUROPE.

Carte Géologique Internationale de l'Europe (Congrès Internationale de Géologie). 1 : 1,500,000. 49 sheets. D. Reimer, Berlin.

Murchison and Nicol, Geological Map of Europe. 1 : 4,800,000. Keith Johnston, Edinburgh.

Dumont, Carte Géologique de l'Europe. 1 : 4,000,000 approx. Noblet, Paris and Liége.

Prestwich, Geological Map of Europe (in Prestwich's 'Geology,' vol. ii.). 1 : 9,500,000 approx. Clarendon Press, Oxford.

Habenicht, Geolog. Karte Europa (in Petermann's 'Mittheilungen,' 1876). 1 : 15,000,000. Justus Perthes, Gotha.

**England and Wales.**— Geological Survey Maps in three scales, 6 inches to a mile, 1 inch to a mile, and $\frac{1}{4}$ inch to a mile.

On the largest scale (1 : 10,560) only maps of the mineral districts are published.
One-inch scale. 110 sheets, old series ; 360 sheets, new series. 1 : 63,360.
General map on scale of $\frac{1}{4}$ inch to a mile. 15 sheets. 1 : 250,000.

Geological Map of England and Wales (A. Geikie). 1 : 633,600. Bartholomew, Edinburgh.

Geological Map of England and Wales (Sir A. Ramsay). 1 : 700,000 approx. Stanford, London.

**Scotland.**—Geological Survey Maps. 131 sheets of 1-inch scale. 1 : 63,360. (Mineral districts, as above.)

Geological Map of Scotland (A. Geikie). 1 : 633,600. Bartholomew, Edinburgh.

**Ireland.**— Geological Survey Maps on the scale of 1 inch to a mile. 205 sheets. 1 : 63,360, as above.

Geological Map of Ireland (E. Hull). 1 : 500,000 approx. Stanford, London.

**France.**—Carte Géologique détaillée de la France (Service de la Carte Géol., Ministère des Travaux Publics). 1 : 80,000. 267 sheets ; smaller scale, 1 : 320,000. 38 sheets ; general map, 1 : 1,000,000. Baudry, Paris.

Vasseur et Carez, Carte Géologique de la France. 1 : 500,000. Comptoir Géologique, Paris.

Levasseur, Carte Géologique de la France. 1 : 3,500,000. De la Grave, Paris.

Carte Géologique de la France. 1841. (Brochant de Villiers, Dufrenoy et E. de Beaumont, Ministère des Travaux Publics). 1 : 500,000. Paris.

**Germany.** — Geologische Specialkarte d. Preussisch. u. d. Thuringisch. Staaten (K. Preuss. Geologisch. Landesanstalt u. Bergakademie). 1 : 25,000. 4500 sheets (including those on same scale of Saxony, Baden, and other States). P. Parey, Berlin ; J. H. Neumann, Berlin.

Lepsius, Geologische Karte d. Deutschen Reichs. 1 : 500,000. 27 sheets. J. Perthes, Gotha.

**Baden.**—Geolog. Specialkarte d. Grossherzogthums Baden (Grossherz. Badisch. Geolog. Landesanstalt). 1 : 25,000. Winter, Heidelberg.

Fraas, Geognostische Wandkarte d. Wurtemberg, Baden, u. Hohenzollern. 1 : 280,000. Schweizerbart, Stuttgart.

**Bavaria.**—Geognostische Karte von Bayern—Gümbel (K. Bayer. Staatsministerium des Innern). 1 : 100,000. Fischer, Cassel.

**Alsace-Lorraine.**—Geolog. Specialkarte von Elsass-Lothringen (Geolog. Landesuntersuchung von Elsass-Lothringen). 1 : 25,000. Schultz, Strassburg.

**Hesse.**—Geolog. Karte des Grossherzogthums Hessen (Grossherzog. Hess. Geolog. Landesanstalt, Ministerium des Innern). 1 : 25,000. Bergstrasser, Darmstadt.

Geolog. Specialkarte des Grossherzogthums Hessen (Mittelrheinisch. Geolog. Verein). 1 : 350,000. Jonghaus, Stuttgart and Darmstadt.

**Saxony.**—Geolog. Specialkarte des Konigreichs Sachsen (Geolog. Landesanstalt des Konigreichs Sachsen). 1 : 25,000. Engelmann, Leipzig.

**Würtemberg.**—Geolog. Specialkartenatlas (K. Würtemberg. Statistisch. Landesamt). 1 : 50,000. Stuttgart.

Übersichtskarte (K. Würtemberg. Statistisch. Landesamt). 1 : 600,000. Stuttgart. See also Baden (Fraas).

**Austria-Hungary.**—Geolog. Specialkarte des Oesterreich.-Ungarisch. Monarchie (KK. Geolog. Reichsanstalt). 1 : 75,000. About 750 sheets, including Hungary, etc. Lechner, Vienna.

Von Hauer, Geolog. Karte von Oesterreich-Ungarn. 1 : 576,000. 12 sheets. Do. 1 : 2,016,000. Hölder, Vienna.

**Hungary.**—Geolog. Karte von Ungarn (K. Ungar. Geolog. Anstalt). 1 : 75,000. (About 350 sheets ; see above.) Do., 1 : 144,000. Buda-Pesth.

Carte Géologique de Hongrie (Société Géologique de Hongrie). 1 : 1,000,000. Kilian, Buda-Pesth.

**Bohemia.**—Geolog. Karte von Böhmen (Comité für die Naturwiss. Landesdurchforschung von Böhmen). 1 : 200,000. Rivnač, Prague.

**Bosnia and Hercegovina.**—Geolog. Karte von Bosnien und der Hercegovina (Geolog. Landesdurchforschung von Bosnien u. Hercegovina). 1 : 75,000. 56 sheets. Sarajevo.

Geol. Map in 'Geologie d. Bosnien-Hercegovina,' by Mojsisovics, Tietze, und Bittner. 1 : 376,000. Hölder, Vienna.

**Galicia.** — Atlas Geologiczny Galicyi (Wydawnictwo Komisyi Fizyjograficznej Akademii Umiejetnosci). 1 : 75,000. 103 sheets. Cracow.

**Roumania.** — Harta Geologica Generala a Romanei (Birone Geologic. Universität, Bucharest). 1 : 200,000. 54 sheets. Bucharest.

**Italy.**—Carta Geologica d'Italia (R. Comitato Geologico, Corpo Reale delle Miniere). 1 : 100,000. 277 sheets. Do., 1 : 1,000,000. 2 sheets. R. Ufficio Geologico, via Sta Susanna, Rome.

**Belgium.**—Carte Géologique de la Belgique (Commission Géologique de la Belgique). 1 : 40,000. 226 sheets. 2 rue Laterale, Brussels. Do. (an earlier survey, 1 : 20,000, not complete, and sheets reproduced on the 1 : 40,000).

Dewalque, Carte Géologique de la Belgique. 1 : 500,000. Vaillant-Carmane, Liége.

**Holland.**—Geolog. Kaart van Nederland (Commissie voor het Geologisch Onderzoek.). 1 : 200,000. 28 sheets. Kruseman, Haarlem.

**Denmark.** — Geologisk Kort over Danemark (Danmarks Geologiske Undersögelse). 1 : 100,000. Reitzel, Copenhagen.

**Sweden.**—Kartor of Sveriges Geologiska Undersökning. Ser. Aa, 1 : 50,000. 350 sheets. Ser. Ab, 1 : 200,000. 90 sheets. Ser. Ac, 1 : 100,000. Norstedt, Stockholm.
Ofversigtskart Sverige Geologiska Undersökning. 1:1,500,000. Norstedt, Stockholm.

**Norway.** — Geol. Rektangelkarter, Norges Geologiske Undersögelse. 1 : 100,000. Christiania.
{Dahll, Nordlige Norge. 1 : 1,000,000. Steenballes, Christiania.
{Kjerulf, Sydlige Norge. 1 : 1,000,000. Steenballes, Christiania.

**Russia.**—Carte Géologique de la Russie (Commission Géologique). 1 : 420,000. 145 sheets. Do., 1 : 2,520,000. Eggers, St. Petersburg.
Geol. Map of Russia in Compt. rend. Congrès Géol. Internat. St. Petersburg, 1897.
Carte des Gîtes Miniers, par De Möller (Départ. des Mines). 1 : 4,200,000. Eggers, St. Petersburg.
**Finland.**—Carte Géologique de la Finlande (Commission Géologique de la Finlande). 1 : 200,000. Do., 1 : 400,000. Helsingfors.

**Spain.**—Mapa Geologico de España (Comision ejecutiva del Mapa Geologico). 1:400,000. In 16 sheets or 64 quarter sheets. Madrid.
Mapa Geologico de España (De Castro: La Comision de Ingenieros de Minas, Ministerio de Fomento). 1 : 1,500,000. Madrid.

**Portugal.**—Carta Geologica de Portugal (Direcção dos Trabalhos Geologicos). 1:500,000. Rua do Arco a Jesus. Lisbon. (See also Spain, De Castro.)

**Greece.**—Peloponnesus in Philippson's *Der Peloponnes*. 1 : 300,000. Friedlander, Berlin.
Attica, in Lepsius' Geologie von Attika (K. Preuss. Akad. Wissenschaft). 1 : 25,000. Reimer, Berlin.

**Switzerland.**—Geolog. Karte der Schweiz (Geolog. Kommission d. Schweiz. Naturforsch. Gesell.). 1 : 100,000. 25 sheets. Do., par Heim & Schmidt. 1 : 500,000. Schmidt & Co., Berne.
Studer and Escher, Geolog. Karte der Schweiz. 1 : 380,000. Do., 1 : 760,000. Würster, Winterthur.

ASIA.

**India.**—Preliminary Sketch Map in Geology of India, 1st edition, issued by the Geol. Survey of India. 1 : 4,000,000 approx. Geol. Map in 2nd edition of Do. 1 : 6,000,000 approx. Geol. Survey Office, Calcutta ; Trübner, London.

**Japan.**—Geological Map of Japan (Imperial Geol. Survey of Japan). 1 : 200,000. Reconnaissance Maps (Do.). 1 : 400,000. General Geological Map (Do.). 1 : 1,000,000. Geol. Survey Institute, Tokyo.

**China.**—Geological Map of part of China in Richthofen's *China*. 1 : 750,000. Reimer, Berlin.

AMERICA, NORTH.

A Catalogue of Geological Maps of North and South America. J. and J. B. Marcou, *Bull. U.S. Geol. Survey*, No. 7 (1884).

**Canada.**—Geological Map Sheets—Nova Scotia, New Brunswick, Ontario (Geological Survey of Canada). 1 : 63,360. Survey Office, Ottawa.
General Geol. Map, 1863 (Geological Survey of Canada). 1 : 7,500,000. Do., Logan, 1866. 1 : 1,500,000. Survey Office, Ottawa.
Geol. Map in 'Esquisse Géologique du Canada,' Logan and Hunt, 1855. 1 : 9,000,000. Bossange, Paris.

**Newfoundland.**—Geol. Map of Newfoundland (Murray, Account of the Geol. Survey of Newfoundland). 1 : 1,584,000. Stanford, London.

**United States.**—Geologic Atlas of the United States, in folio parts (United States Geological Survey). Various scales. Geol. Survey Office, Washington.

General Geological Map of the United States, reduced from the Geol. Survey Sheets by W J M'Gee.

General Geological Map of the United States (Hitchcock, American Inst. of Mining Engineers, 1886). 1 : 7,000,000. Amer. Inst. Mining Engineers Office, New York.

## AMERICA, CENTRAL.

**Mexico.**—Bosquejo de Una Carta Geologica de la Republica Mexicana (Castillo Instituto Geologico de Mexico). 1 : 3,000,000. Inst. Geol., Secretario de Fomento, Mexico.

**Jamaica.**—Geol. Map (Sawkins and C. B. Brown, 1865, Geol. Survey of the West Indies). 1 : 250,000. Ordnance Survey Office, Southampton, Eng.

**Trinidad.**—Geol. Map (Wall and Sawkins, 1860, Geol. Survey of the West Indies). 1 : 250,000. Ordnance Survey Office, Southampton, Eng.

**Barbadoes.**—Geol. Map (Harrison and Jukes-Browne). 1 : 500,000. ?

## AMERICA, SOUTH.

Geolog. Übersichtskarte des Mittleren Theiles von Süd-Amerika (Haidinger and Foetterle), 1854. 1 : 15,000,000. KK. Geol. Inst. Vienna.

**Argentina.**—Mapa Geologico del Interior de la Republica Argentina (Brackenbusch). 1 : 1,000,000. Hellfarth, Gotha.

**British Guiana.**—Geol. Map of Brit. Guiana (Sawkins, 1870). 1 : 1,000,000.

Geol. Map of Brit. Guiana (Geol. Survey of Brit. Guiana, Brown, 1873). 1 : 900,000. Ordnance Survey Office, Southampton, Eng.

**Chili.**—Carte Géol. in Pissis' 'Description Géolog. de la République de Chili,' 1851. 1 : 200,000. Santiago.

## AFRICA.

**Egypt.**—Carte Géol. de l'Egypte, de l'Arabie Pétrée et de la Palestine (Figari Bey, Études Géologiques de l'Egypte, etc., 1864). 1 : 300,000 approx.

Carte Géol. de l'Egypte, etc. (Zagiell, in 'Aperçu Géologique des Formations Géol. de l'Egypte, etc.' 1872). 1 : 2,000,000.

**Algeria.**—Carte Géologique de l'Algérie (Service de la Carte Géol.). 1 : 50,000. Baudry, Paris.

Carte Géologique Provisoire (Pomel and others). 1 : 800,000. Jourdan, Algiers.

**South Africa.**—Geological Map of South Africa (Dunn). 1 : 2,000,000. Stanford, London.

Carte Géolog. du Transvaal (Molengraaf, 'Esquisse Géol. de la Republique du Transvaal,' *Bull. Soc. Géol. France*, 1901). 1 : 1,500,000. Soc. Géol. France, Paris.

Geological Map of the Transvaal (Struben). 1 : 1,250,000. Wyld, London.

## AUSTRALASIA.

**New South Wales.**—Geological Map of New South Wales (Geol. Survey of N.S.W.). 1 : 506,880. Do., 1 : 077,120. Do., 1 : 1,393,920. Dept. of Mines and Agriculture, Sydney.

**Victoria.**—Geolog. Map of Victoria in quarter-sheets (Geol. Survey of Victoria). 1 : 125,000. Do., 1 : 506,880. Do., 1 : 1,013,760. Dept. of Mines, Melbourne.

**South Australia.**—Geol. Map of S. Australia (Geol. Survey of South Australia). 1 : 1,013,760. Do., 1 : 2,534,400. Dept. of Crown Lands and Mines, Adelaide.

**Queensland.**—Geolog. Map of Queensland (Geol. Surv. of Queensland). 1 : 584,000. Dept. of Public Works and Mines, Brisbane.

**West Australia.**—Geolog. Map of West Australia (Geol. Surv. of W. Australia). 1 : 3,000,000. Geolog. Office, Perth; Philip, London.

**Tasmania.**—Geol. Map in R. M. Johnston's 'Geology of Tasmania,' 1888. 1 : 1,150,000. Hobart, Tasmania.

**New Zealand.**—Geol. Map of New Zealand (Geol. Survey of N.Z.). 1 : 2,000,000. Geol. Survey Office, Wellington.

In addition to the maps there are for some countries special treatises on their geology, such as H. B. Woodward's 'Geology of England and Wales,' and Lepsius' 'Geologie von Deutschland.' To some of these reference will be made in the course of this volume. The student will obtain much help from an excellent series of geological guides published by Messrs. Borntraeger of Berlin, of which ten have been issued dealing with the districts of Dresden, Mecklenburg, Bornholm, Pomerania, Alsace, Riesengebirge, Scania, Campania, the Alps, etc.

# BOOK I.

## COSMICAL ASPECTS OF GEOLOGY.

BEFORE geology had attained to the position of an inductive science, it was customary to begin all investigations into the history of the earth by propounding or adopting some more or less fanciful hypothesis, in explanation of the origin of our planet or of the universe. Such preliminary notions were looked upon as essential to a right understanding of the manner in which the materials of the globe had been put together. To the illustrious James Hutton (1785) geologists are indebted, if not for originating, at least for strenuously upholding, the doctrine that it is no part of the province of geology to discuss the origin of things. He taught them that in the materials from which geological evidence is to be compiled there can be found "no traces of a beginning, no prospect of an end." In England, mainly to the influence of the school which he founded, and to the subsequent rise of the Geological Society (1807), which resolved to collect facts instead of fighting over hypotheses, is due the disappearance of the crude and unscientific cosmologies of previous centuries.

But there can now be little doubt that in the reaction against the visionary and often grotesque speculations of earlier writers, geologists were carried too far in an opposite direction. In allowing themselves to believe that geology had nothing to do with questions of cosmogony, they gradually grew up in the conviction that such questions could never be other than mere speculation, interesting or amusing as a theme for the employment of the fancy, but hardly coming within the domain of sober and inductive science. Nor would they soon have been awakened out of this belief by anything in their own science. It is still true that in the data with which they are accustomed to deal, as comprising the sum of geological evidence, there can be found no trace of a beginning, though there is ample proof of constant, upward progression from some invisible starting-point. The oldest sedimentary rocks which have been discovered on any part of the globe have, no doubt, been derived from other rocks older than themselves, while the oldest known eruptive rocks differ in no essential particular from those of later periods and give no clue to the

original constitution of the planet. Geology by itself has not yet revealed, and is little likely ever to reveal, a portion of the first solid crust of our globe. If, then, geological history is to be compiled from direct evidence furnished by the rocks of the earth, it cannot begin at the beginning of things, but must be content to date its first chapter from the earliest period of which any record has been preserved among the rocks.

Nevertheless, though, in its usual restricted sense, geology has been, and must ever be, unable to reveal the earliest history of our planet, it no longer ignores, as mere speculation, what is attempted in this subject by its sister sciences. Astronomy, physics, and chemistry have in late years all contributed to cast much light on the earliest stages of the earth's existence, previous to the beginning of what is commonly regarded as geological history. Whatever extends our knowledge of the former conditions of our globe may be legitimately claimed as part of the domain of geological inquiry. If Geology, therefore, is to continue worthy of its name as the science of the earth, it must take cognisance of these recent contributions from other sciences. It can no longer be content to begin its annals with the records of the oldest rocks, but must endeavour to grope its way through the ages which preceded the formation of any rocks. Thanks to the results achieved with the telescope, the spectroscope, and the chemical laboratory, the story of these earliest ages of our earth is every year becoming more definite and intelligible.

## I. Relations of the Earth in the Solar System.

As a prelude to the study of the structure and history of the earth, some of the general relations of our planet to the solar system may here be noticed. The investigations of recent years, showing the community of substance between the different members of that system, have revived and have given a new form and meaning to the well-known nebular hypothesis of Kant, Laplace, and W. Herschel, which sketched the progress of the system from the state of an original nebula to its existing condition of a central incandescent sun with surrounding cool planetary bodies. According to this hypothesis, the nebula, originally diffused at least as far as the furthest member of the system, began to condense towards the centre, and in so doing threw off or left behind successive rings. These, on disruption and further condensation, assumed the form of planets, sometimes with a further formation of rings, which in the case of Saturn remain, though in other planets they have broken up and united into satellites.[1]

[1] The validity of the nebular hypothesis as ordinarily understood has recently been challenged by Dr. F. R. Moulton, who has brought forward calculations and arguments which, if sustained, will require considerable modification of the computations that have been made as to the heat that the sun has radiated, and as to the age of the earth ("An Attempt to test the Nebular Hypothesis by an appeal to the Laws of Dynamics," *Astrophysical Journal*, Chicago, vol. xi. (1900), pp. 103-130). The hypothesis has also been simultaneously attacked by Professor Chamberlin ("An Attempt to test the Nebular Hypothesis by the relations of Masses and Momenta," *Journ. Geol.*, Chicago, viii. (1900), pp. 58-73).

Accepting this view, we might expect the matter composing the various members of the solar system to be everywhere essentially similar The fact of condensation round centres, however, indicates probable differences of density throughout the nebula. That the materials composing the nebula may have arranged themselves according to their respective densities, the lightest occupying the exterior, and the heaviest the interior of the mass, is suggested by a comparison of the densities of the various planets. These densities are usually estimated as in the following table, that of the earth being taken as the unit :—

| | | |
|---|---|---|
| Density of the Sun | | 0·25 |
| ,, | Mercury | 1·12 |
| ,, | Venus | 1·03 |
| ,, | Earth | 1·00 |
| ,, | Mars | 0·70 |
| ,, | Jupiter | 0·24 |
| ,, | Saturn | 0·13 |
| ,, | Uranus | 0·17 |
| ,, | Neptune | 0·16 |

It is to be observed, however, that "the densities here given are mean densities, assuming that the *apparent* size of the planet or sun is the *true* size, *i.e.* making no allowance for thousands of miles deep of cloudy atmosphere. Hence the numbers for Jupiter, Saturn, and Uranus are certainly too small, that for the sun, much too small." [1] Taking the figures as they stand, while they do not indicate a strict progression in the diminution of density, they state that the planets near the sun possess a density about twice as great as that of granite, but that those lying towards the outer limits of the system are composed of matter as light as cork. Again, in some cases, a similar relation has been observed between the densities of the satellites and their primaries. The moon, for example, has a density little more than half that of the earth. The first satellite of Jupiter is less dense, though the other three are said to be more dense, than the planet. Further, in the condition of the earth itself, a very light gaseous atmosphere forms the outer portion, beneath which lies a heavier layer of water, while within these two envelopes the materials forming the solid substance of the planet are so arranged that the outer layer or crust has only about half the density of the whole globe.

According to the hypothesis now under consideration, it is conceived that, in the gradual condensation of the original nebula, whether composed of incandescent gas or of swarms of meteorites reduced to a vapourous condition by collision, each successive mass left behind represented the density of its parent shell, and consisted of progressively heavier matter.[2] The remoter planets, with their low densities and vast

[1] Professor Tait, MS. note.

[2] On the origin of Satellites, see the researches of Professor G. H. Darwin, *Phil. Trans.* clxx. (1879), p. 585 ; *Proc. Roy. Soc.* xxx. p. 1 ; also his papers, "On figures of Equilibrium of rotating Masses of Fluid," *Phil. Trans.* clxxviii. (1887) ; and "On the Mechanical Condition of a Swarm of Meteorites and on the Theories of Cosmogony," *Phil. Trans.* clxxx. (1889).

absorbing atmospheres, may be supposed to consist of metalloids, like the outer part of the sun's atmosphere, while the interior planets are no doubt mainly metallic. The rupture of each planetary ring would, it is thought, raise the temperature of the resultant nebulous planet to such a height as to allow the vapours to rearrange themselves by degrees in successive layers, or rather shells, according to densities. And when the planet gave off a satellite, that body might be expected to possess the composition and density of the outer layers of its primary.[1]

For many years, the only evidence available as to the actual composition of other heavenly bodies than our own earth was furnished by the *meteorites*, or falling stars, which from time to time have entered our atmosphere from planetary space, and have descended upon the surface of the globe.[2] Subjected to chemical analysis, these foreign bodies show considerable diversities of composition; but in no case have they yet revealed the existence of any element not already recognised among terrestrial materials. They have been classified in three groups: *Siderites* or *holosiderites*, composed wholly or chiefly of iron; *Siderolites*, consisting partly of iron and partly of various stony materials; and *Aerolites*, formed almost entirely of such stony minerals. These groups pass into each other, and examples of more than one of them may occur in the same meteoric fall. Of the twenty-five terrestrial elements which have been detected in meteorites the most frequent are iron, nickel, phosphorus, sulphur, carbon, oxygen, silicon, magnesium, calcium, and aluminium. Less frequent or occurring in smaller quantities are hydrogen, nitrogen, chlorine, lithium, sodium, potassium, titanium, chromium, manganese, cobalt, arsenic, antimony, tin, and copper. These various elements occur for the most part in a state of combination. The iron, as an alloy with nickel, is the most abundant constituent of meteorites, inasmuch as it exceeds all the others put together. The phosphorus is combined with

1 Sir Norman Lockyer, 'The Chemistry of the Sun' (1887); 'The Meteoritic Hypothesis' (1890); 'The Sun's Place in Nature' (1897). Readers interested in the historical development of geological opinion will find much suggestive matter, bearing on the questions discussed above, in De la Beche's 'Researches in Theoretical Geology,' 1834,—a work notably in advance of its time.

2 On meteorites consult Partsch, 'Die Meteoriten,' Vienna, 1843. Rose, *Abhand. königl. Akad. Berlin*, 1863. Rammelsberg, 'Die Chemische Natur der Meteoriten,' 1870-79. Tschermak, *Sitzb. Akad. Wissen.*, Vienna (1875), lxxi.; 'Die Mikroskopische Beschaffenheit der Meteoriten,' Stuttgart, 1885. A. E. Nordenskiöld, 'Studier och Forskningar föranledda af mina Resor i Höga Norden,' Stockholm, 1883, where at pp. 127-227 an interesting discussion is given of the geological significance of the cosmic matter that falls to the earth's surface, especially with regard to the Kant-Laplace nebular hypothesis. Daubrée, 'Etudes Synthétiques de Géologie Expérimentale,' 1879; 'Régions invisibles du Globe,' 1892. Brezina and Cohen, 'Die Structur und Zusammensetzung der Meteoreisen,' Stuttgart, 1886. E. Cohen, "Meteoreisen-studien," in *Ann. K. K. Naturh. Hofmuseums*, Vienna. W. Flight, *Geol. Mag.* 1875; *Pop. Sci. Rev.* new ser. i. p. 390; *Proc. Roy. Soc.* xxxiii. p. 343. A. W. Wright, *Amer. Journ.* ser. 3, xi. p. 253; xii. p. 165. L. Fletcher, "An Introduction to the Study of Meteorites," *British Museum Catalogue*, 1886. O. C. Farrington, *Journ. Geol.* v. (1897), p. 126; ix. pp. 51, 174, 393, 522, 623. A useful compendium of information on this subject will be found in E. A. Wülfing's 'Die Meteoriten in Sammlungen und ihre Literatur,' pp. xlvi, 460, Tübingen, 1897.

nickel and iron, the silicon with oxygen and various bases. A few of the elements occur in a free state. Thus hydrogen and nitrogen are found as occluded gases and carbon as graphite, rarely as diamond. Of combinations of elements in meteorites, some, not yet recognised among terrestrial minerals, comprise alloys of iron and nickel and various sulphides and silicates. But others have been identified with well-known minerals of the earth's crust, including olivine (which comes next in abundance after iron-nickel), orthorhombic and monoclinic pyroxenes, plagioclase, tridymite, magnetite, chromite, etc. There is likewise a carbonaceous group of meteorites containing carbon, both amorphous and as diamond, also combined with hydrogen and oxygen, and in some cases combustible, with a bituminous smell. All meteorites hitherto examined evolve gas on heating. The occluded gases consist of hydrogen, carbon monoxide, carbon dioxide, nitrogen, and marsh gas, the amount varying from less than one volume to upwards of forty-seven volumes, the average proportion from iron and stone meteorites being 2·82 volumes.

Meteorites present some structures closely resembling those of terrestrial igneous rocks. Thus a structure nearly the same as that of basalt has been found among them, while many of the siderites are perfectly like the iron-masses found in the basalts of Greenland.[1] But certain meteoritic structures appear to be peculiar. Such are the well-known Widmanstätten figures on the nickel-irons, and also the curious rounded bodies known as "chondres." Many meteorites contain true glass, and a fragmental structure like that of volcanic breccia or tuff is by no means rare.

Various theories have been propounded as to the origin or source of those bodies which come to our planet from space. But at present we possess no satisfactory basis of fact on which to speculate. Whether these stones belong to the solar system, or reach us from remoter space, they prove that some at least of the elements and minerals with which we are familiar extend beyond our planet.

But, in recent years, a far more precise and generally available method of research into the composition of the heavenly bodies has been found in the application of the spectroscope. By means of this instrument, the light emitted from self-luminous bodies can be analysed in such a way as to show what elements are present in their intensely hot luminous vapour. When the light of the incandescent vapour of a metal is allowed to pass through a properly arranged prism, it is seen to give a spectrum consisting of transverse bright lines only. This is termed a *radiation-spectrum.* Each element appears to have its own characteristic arrangement of lines, which in general retain the same relative position, intensity, and colours. Moreover, gases and the vapours of solid bodies are found to intercept those rays of light which they themselves emit. The spectrum of sodium-vapour, for example, shows among others two bright orange lines. If therefore white light, from some hotter light-source, passes through the vapour of sodium, these two bright lines became dark lines, the light being exactly cut off which would have been given out by the sodium itself. This is called an *absorption-spectrum.*

[1] O. C. Farrington, *Journ. Geol.* ix. pp. 52, 57, 174.

From this method of examination, it has been inferred that many of the elements of which our earth is composed must exist in the state of incandescent vapour in the atmosphere of the sun. Thirty-two metals have thus been identified, including aluminium, barium, manganese, lead, calcium, cobalt, potassium, iron, zinc, copper, nickel, sodium, and magnesium. These elements, or at least substances which give the same groups of lines as the terrestrial elements with which they have been identified, do not occur promiscuously diffused throughout the outer mass of the sun. According to Sir Norman Lockyer's first observations, they appear to succeed each other in relation to their respective densities. Thus the coronal atmosphere which, as seen in total eclipses, extends to so prodigious a distance beyond the disc of the sun, consists mainly of subincandescent hydrogen and another element which may be new. Beneath this external vaporous envelope lies the chromosphere, where the vapours of incandescent hydrogen, calcium, and magnesium can be detected. Further inward the spot-zone shows the presence of sodium, titanium, etc.; while still lower, a layer (the *reversing* layer) of intensely hot vapours, lying probably next to the inner brilliant photosphere, gives spectroscopic evidence of the existence of incandescent iron, manganese, cobalt, nickel, copper, and other well-known terrestrial metals.[1]

It is to be observed, however, that in these spectroscopic researches the decomposition of the elements by electrical action was not considered. The conclusions embodied in the foregoing paragraph have been founded on the idea that the lines seen in the spectrum of any element are all due to the vibrations of the molecules of that element. But Sir Norman Lockyer has suggested that this view may after all be but a rough approximation to the truth; that it may be more accurate to say, as a result of the facts already acquired, that there exist basic elements common to calcium, iron, etc., and to the solar atmosphere, and that the spectrum of each body is a summation of the spectra of various molecular complexities which can exist at different temperatures, the simplest only being found in the hottest part of the sun.[2]

The spectroscope has likewise been successfully applied by Sir William Huggins and others to the observation of the fixed stars and nebulæ, with the result of establishing a similarity of elements between our own system and other bodies in sidereal space. In the radiation spectra of nebulæ, Sir William finds the hydrogen lines very prominent; and he conceives that they may be glowing masses of that element. Professor Tait has suggested, on the other hand, that they are more probably clouds of stones frequently colliding and thus giving off incandescent gases. Sir William Thomson (now Lord Kelvin) favours this

[1] On spectroscopic research as applied to the sun, see Kirchhoff and Bunsen, 'Researches on Solar Spectrum,' etc., 1863; Ångström, 'Recherches sur le Spectre normal du Soleil'; Sir N. Lockyer's works, cited on p. 16, and 'Studies in Spectrum Analysis' (International Series), 1878; Sir W. Huggins and Miller, *Proc. Roy. Soc.* xii., *Phil. Trans.* 1864; Sir Henry Roscoe's 'Spectrum Analysis,' with authorities there cited.

[2] See also the opposite views of Dewar and Liveing, *Proc. Roy. Soc.* xxx. p. 93, and H. W. Vogel, *Nature*, xxvii. p. 233.

view, which is further amply supported by spectroscopic observations. Among the fixed stars, absorption-spectra have been recognised, pointing to a structure resembling that of our sun, viz. an incandescent nucleus which may be solid or liquid or of very highly compressed gas, but which gives a continuous spectrum and which is surrounded with an atmosphere of glowing vapour.[1] Those stars which show the simplest spectra are believed to have the highest temperature, and in proportion as they cool their materials will become more and more differentiated into what we call elements. The most brilliant or hottest stars show in their spectra only the lines of gases, as hydrogen. Cooler stars, like our sun, give indications of the presence, in addition, of the metals—magnesium, sodium, calcium, iron. A still lower temperature is marked by the appearance of the other metals, metalloids, and compounds.[2] The sun would thus be a star considerably advanced in the process of differentiation or association of its atoms. It contains, so far as we know, no metalloid except carbon, and possibly oxygen, nor any compound; while stars like Sirius show the presence only of hydrogen, with but a feeble proportion of metallic vapours; and on the other hand, the red stars indicate by their spectra that their metallic vapours have entered into combination, whence it is inferred that their temperature is lower than that of our sun.

More recently, however, another view of the evolution of stars has been propounded by Sir Norman Lockyer. He conceives that all self-luminous cosmical bodies are composed either of swarms of meteorites, or of masses of vapour produced by collisions of meteorites; that stars, comets, and nebulæ are only different phases of the same series of changes; that where the temperature of a star is increasing, the star consists of a meteor-swarm, which by constant collision of its individual meteorites is gradually being vapourised by heat; and that after volatilisation cooling sets in and the vapour finally condenses into a globe.[3]

## II. Form and Size of the Earth.

Further confirmation of some of the foregoing views as to the order of planetary evolution is furnished by the form of the earth and the arrangement of its component materials.

That the earth is an oblate spheroid, and not a perfectly spherical globe, was discovered and demonstrated by Newton. He even calculated the amount of ellipticity long before any measurement had confirmed such a conclusion. During the past century numerous arcs of the meridian were measured, chiefly in the northern hemisphere. From a

[1] Sir W. Huggins, *Proc. Roy. Soc.* 1863-66, and *Brit. Assoc. Lecture* (Nottingham, 1866); Sir W. Huggins and Miller, *Phil. Trans.* 1864.

[2] Sir N. Lockyer, *Comptes rendus*, Dec. 1873.

[3] 'The Meteoritic Hypothesis,' 1890. Prof. G. H. Darwin, in a paper "On the Mechanical Conditions of a Swarm of Meteorites, and on the Theories of Cosmogony," *Phil. Trans.* clxxx. (1889), pp. 1-69, has proposed an explanation whereby the nebular and meteoritic hypotheses may be combined.

series made by different observers between the latitudes of Sweden and the Cape of Good Hope, Bessel obtained the following data for the dimensions of the earth:—

| | | |
|---|---|---|
| Equatorial diameter . . | 41,847,192 feet, or | 7925·604 miles. |
| Polar diameter . . . | 41,707,314 ,, | 7899·114 ,, |
| Amount of polar flattening . | 139,768 ,, | 26·471 ,, |

The equatorial circumference is thus a little less than 25,000 miles, and the difference between the polar and equatorial diameters (nearly 26½ miles) amounts to about $\frac{1}{300}$th of the equatorial diameter.[1] More recently, however, it has been shown that the oblate spheroid indicated by these measurements is not a symmetrical body, the equatorial circumference being an ellipse instead of a circle. The greater axis of the equator lies in long. 8° 15′ W.—a meridian passing through Ireland, Portugal, and the north-west corner of Africa, and cutting off the north-east corner of Asia in the opposite hemisphere.[2]

The polar flattening, established by measurement and calculation as that which would necessarily have been assumed by an originally plastic globe in obedience to the movement of rotation, has been cited as evidence that the earth was once in a plastic condition. Taken in connection with the analogies supplied by the sun and other heavenly bodies, this inference appeared to be well grounded.[3] More recently, however, it has been contended that even in a truly solid body a polar flattening might be developed under the influence of rotation.[4]

Though the general spheroidal form of our planet, and probably the general distribution of sea and land, are referable to the early effects of rotation on a gaseous, fluid, or viscous mass, the present details of its surface-contours appear to be of comparatively recent date. Speculations have been made as to what may have been the earliest character of the solid surface, whether it was smooth or rough, and particularly whether it was marked by any indication of the existing continental elevations and oceanic depressions. So far as we can reason from geological evidence, there is no proof of any uniform superficies having ever

[1] Herschel, 'Astronomy,' p. 139.

[2] A. R. Clarke, *Phil. Mag.* August 1878; *Encyclopædia Britannica*, 9th edit. x. 172. See the latest discussion of this subject in Major Burrard's 'The Attractions of the Himalaya Mountains upon the Plumb-line in India: Considerations of Recent Data,' Dehra Dun, 1901.

[3] It was opposed by Mohr ('Geschichte der Erde,' p. 472), who, adopting a suggestion long ago made by Playfair, endeavoured to show that the polar flattening can be accounted for by greater denudation of the polar tracts, exposed as these have been by the heaping up of the oceanic waters towards the equator in consequence of rotation. He dwelt chiefly on the effects of glaciers in lowering the land; but as Pfaff has pointed out, the work of erosion is chiefly performed by other atmospheric forces that operate rather towards the equator than the poles ('Allgemeine Geologie als exacte Wissenschaft,' p. 6). Compare Naumann, *Neues Jahrb.* 1871, p. 250. Nevertheless, Mohr undoubtedly recalled attention to a conceivable cause by which, in spite of polar elevation or equatorial subsidence, the external form of the planet might be preserved.

[4] See in particular the papers by Mr. C. Chree, *Phil. Mag.* 1891, pp. 233 and 342.

existed. Most probably the first formed crust was broken up irregularly, and not until after many successive corrugations did the surface acquire stability. Some writers have imagined that at first the ocean spread over the whole surface of the planet. But of this there is not only no evidence, but good reason for believing that it never could have taken place. As will be alluded to in a later page, the preponderance of water in the southern hemisphere seems to indicate some excess of density in that hemisphere. This excess can hardly have been produced by any change since the materials of the interior ceased to be mobile; it must therefore be at least as ancient as the condensation of water on the earth's surface. Hence there was probably from the beginning a tendency in the ocean to accumulate in the southern rather than in the northern hemisphere.

That land existed from the earliest ages of which we have any record in rock-formations, is evident from the obvious fact that these formations themselves consist in great measure of materials derived from the waste of land. When the student, in a later part of this volume, is presented with the proofs of the existence of enormous masses of sedimentary deposits, even among some of the oldest geologial systems, he will perceive how important must have been the tracts of land that could furnish such piles of detritus.

An ingenious speculation was published many years ago by W. Lowthian Green, who, long resident at Honolulu as minister of foreign affairs to the King of the Sandwich Islands, had his attention directed to geophysical problems by the remarkable volcanic phenomena of these islands.[1] Starting from the ideas propounded by Élie de Beaumont with regard to his *reseau pentagonal*, by which the distinguished French geologist endeavoured to account for the distribution of the leading structural lines on the surface of the globe, Mr. Green claimed that the only geometrical figure which will fit and explain these lines is the six-faced tetrahedron, a form which he conceived to have resulted from the collapse of the terrestrial crust upon the liquid interior. He proceeded to show how the four great continental masses of land were distributed about the four acute solid angles of the tetrahedron, and how the four principal oceans ranged themselves on the four obtuse solid angles. Moreover, he regarded this fundamental geometric form as having undergone a certain amount of deformation from the effects of rotation, to which cause he ascribed the eastward deviation of the southern parts of the continents, and likewise the great line or plane of lateral shift which is traceable along the line of the Mediterranean Sea, by the Persian Gulf to the East Indies, and thence by New Guinea and the Solomon Islands across the Pacific Ocean, Central America, the West Indian Islands, and the Atlantic back to the Mediterranean. Mr. Green's suggestion has in recent years been revived and applied by different writers in explanation

[1] His ideas were first broached in an article published in 1857 in the *Edinburgh New Philosophical Journal*, and were subsequently elaborated in his work, 'Vestiges of the Molten Globe,' of which the first part was published in London in 1875 and the second and much larger part at Honolulu in 1887.

of the distribution of land and sea and the positions of lines of volcanic energy.[1]

## III. The Movements of the Earth in their Geological Relations.

We are here concerned with the earth's motions in so far only as they materially influence the progress of geological phenomena.

§ 1. **Rotation.**—In consequence of its angular momentum at its original separation, the earth rotates on its axis.[2] The rate of rotation has once been much more rapid than it now is (p. 30). At present a complete rotation is performed in about twenty-four hours, and to it is due the succession of day and night. So far as observation has yet gone, this movement is uniform, though recent calculations of the influence of the tides in retarding rotation tend to show that a very slow diminution of the angular velocity is in progress. If this be so, the length of the day and night will slowly increase, until finally the duration of the day and that of the year will be equal. The earth will then have reached the condition into which the moon has passed relatively to the earth, one half being in continual day, the other in perpetual night

The linear velocity due to rotation varies in different places, according to their position on the surface of the planet. At each pole there can be no velocity, but from these two points towards the equator there is a continually increasing rapidity of motion, till at the equator it is equal to a rate of 507 yards in a second.

To the rotation of the earth are due certain remarkable influences upon currents of air circulating either towards the equator or towards the poles. Currents which move from polar latitudes travel from parts of the earth's surface where the velocity due to rotation is small, to others where it is great. Hence they lag behind, and their course is bent more and more westward. An air current, quitting the north polar or north temperate regions as a north wind, is deflected out of its course, and becomes a north-east wind. On the opposite side of the equator, a similar current, setting out straight for the equator, is changed into a south-east wind. Hence, as is well known, the trade-winds have their characteristic westward deflection. On the other hand a current setting out northwards or southwards from the equator, passes into regions having a less velocity due to rotation than it possesses itself, and hence it travels on in advance and appears to be gradually deflected eastward. The aerial currents, blowing steadily across the surface of the ocean towards the

[1] See, in particular, A. de Lapparent's 'Traité de Geologie'; Michel Lévy, *B.S.G. France*, t. xxvi. (1898), p. 105; J. W. Gregory, *Journ. Roy. Geog. Soc.* xiii. (1899), p. 225; M. Bertrand, *Compt. rend.* February 1900; B. K. Emerson, *Bull. Amer. Geol. Soc.* xi. (1901), p. 61; C. H. Hitchcock, *Amer. Geol.* xxv. (January 1900), p. 1; C. R. Keyes, *Journ. Geol.* x. (1901), p. 244.

[2] The recent observation of periodical variations of terrestrial latitudes noticed *postea*, p. 25, demands, according to Professor Sloudski of Moscow, a revision of the actual theory of the rotation of our planet. *Nature*, liv. (1896), p. 161.

equator, produce oceanic currents which unite to form the westward-flowing equatorial current.

It has been maintained by Von Baer[1] that a certain deflection is experienced by rivers that flow in a meridional direction, like the Volga and Irtisch. Those travelling polewards are asserted to press upon their eastern rather than their western banks, while those which run in the opposite direction are stated to be thrown more against the western than the eastern. When, however, we consider the comparatively small volume, slow motion, and continually meandering course of rivers, it may reasonably be doubted whether this *vera causa* can have had much effect generally in modifying the form of river-channels.

§ 2. **Revolution.**—Besides turning on its axis, the globe performs a movement round the sun, termed revolution. This movement, accomplished in rather more than 365 days, determines for us the length of our year, which is, in fact, merely the time required for one complete revolution. The path or orbit followed by the earth round the sun is not a perfect circle but an ellipse, with the sun in one of the foci, the mean distance of the earth from the sun being 92,800,000, the present aphelion distance 94,500,000, and the perihelion distance 91,250,000 miles. By slow secular variations, the form of the orbit alternately approaches to and recedes from that of a circle. At the nearest possible approach between the two bodies, owing to change in the ellipticity of the orbit, the earth is 14,368,200 miles nearer the sun than when at its greatest possible distance. These maxima and minima of distance occur at vast intervals of time.[2] The last considerable eccentricity took place about 200,000 years ago, and the previous one more than half a million years earlier. Since the amount of heat received by the earth from the sun is inversely as the square of the distance, eccentricity may have had in past time some effect upon the climates of the earth.

§ 3. **Precession of the Equinoxes.**—If the axis of the earth were perpendicular to the plane of its orbit, there would be equal day and night all the year round. But it is really inclined from that position at an angle of 23° 27′ 21″. Hence our hemisphere is alternately presented to and turned away from the sun, and, in this way, brings the familiar alternation of the seasons. Again, were the earth a perfect sphere, of uniform density throughout, the position of its axis of rotation would not be changed by attractions of external bodies. But owing to the protuberance along the equatorial regions, the attraction chiefly of the

[1] "Ueber ein allgemeines Gesetz in der Gestaltung der Flussbetten," *Bull. Acad. St. Pétersbourg*, ii. (1860). See also Ferrel on the motion of fluids and solids relatively to the earth's surface, *Camb. (Mass.) Math. Monthly*, vols. i. and ii. (1859-60); Dulk, *Z. Deutsch. Geol. Ges.* xxxi. (1879), p. 224. The river Irtisch is said in flowing northward to have cut so much into its right bank that villages are gradually driven eastwards, Demiansk having been shifted about a mile in 240 years (*Nature*, xv. p. 207). But this may be accounted for by local causes. See an excellent paper on this subject with special reference to the régime of some rivers in Northern Germany, by F. Klockmann, *Jahrb. Preuss. Geol. Landesanst.* 1882; also E. Dunker, *Zeitsch. für die gesammten Naturwissenschaften*, 1875, p. 463; G. K. Gilbert, *Amer. Jour. Sci.* xxvii. (1884), p. 427.

[2] See Croll's 'Climate and Time,' chaps. iv., xix.

moon and sun tends to pull the axis aside, or to make it describe a conical movement, like that of the axis of a top, round the vertical. Hence each pole points successively to different stars. This movement, called the precession of the equinoxes, in combination with another smaller movement, due to the attraction of the moon, completes its cycle in 21,000 years, the annual total advance of the equinox amounting to 62″. At present the winter in the northern hemisphere coincides with the earth's nearest approach to the sun, or *perihelion*. In 10,500 years hence it will take place when the earth is at the farthest part of its orbit from the sun, or in *aphelion*. This movement was believed by Croll to have had great importance in connection with former secular variations in the eccentricity of the orbit.

§ 4. **Change in the Obliquity of the Ecliptic.**—The angle at which the axis of the earth is inclined to the plane of its orbit does not remain strictly constant. It oscillates through long periods of time to the extent of about a degree and a half, or perhaps a little more, on either side of the mean. According to Croll,[1] this oscillation has considerably affected former conditions of climate on the earth, since, when the obliquity is at its maximum, the polar regions receive about eight and a half days' more of heat than they do at present—that is, about as much heat as lat. 76° enjoys at this day. He thought that this movement may have augmented the geological effects of precession, to which reference has just been made.

§ 5. **Stability of the Earth's Axis.**—That the axis of the earth's rotation has successively shifted, and consequently that the poles have wandered to different points on the surface of the globe, has been maintained by geologists as the only possible explanation of certain remarkable conditions of climate, which can be proved to have formerly obtained within the Arctic Circle. Even as far north as lat. 81° 45′, abundant remains of a vegetation indicative of a warm climate, and including a bed of coal 25 to 30 feet thick, have been found *in situ*.[2] It is contended that when these plants lived, the ground could not have been permanently frozen or covered for most of the year with thick snow. In explanation of the difficulty, it has been suggested that the north pole did not occupy its present position, and that the locality where the plants occur lay in more southerly latitudes. Without at present entering on the discussion of the question whether the geological evidence necessarily requires so important a geographical change, let us consider how far a shifting of the axis of rotation has been a possible cause of change during that section of geological time for which there are records among the stratified rocks.

From the time of Laplace,[3] astronomers have strenuously denied the possibility of any sensible change in the position of the axis of rotation. In recent years, indeed, by the greatly increased precision of the instruments of observation, it has been ascertained that this position is not really uniform. Lord Kelvin had already pointed out that it is probably affected by the movements of large bodies of water and air over the earth's sur-

[1] *Trans. Geol. Soc. Glasgow*, ii. p. 117. 'Climate and Time,' chap. xxv.

[2] Fielden and Heer, *Quart. Journ. Geol. Soc.* Nov. 1877.

[3] 'Mécanique Céleste,' tome v. p. 14.

face and by the effects of the enormous periodical accumulations of snow and ice, whereby what had been supposed to be a simple and regular movement becomes complicated. Investigations have lately been undertaken to ascertain the nature and amount of the deviation, and by the co-operation of a number of observatories clear evidence has been obtained that such displacements actually occur. From the results of nearly 6000 observations made at Kasan, in Eastern Russia, at Strasburg and Bethlehem, Pennsylvania, it appears that the amplitude of the movement of the pole on the surface of the earth is between 40 and 50 feet. The movement is curiously irregular and somewhat spiral.[1]

These proved variations in the position of the earth's axis of rotation seem to be too slight to possess much effect in the production of geological changes. With regard to more serious shifting, it has been urged that, since the planet acquired its present oblate spheroidal form, nothing but an utterly incredible amount of deformation could overcome the greater centrifugal force of the equatorial protuberance. It is certain, however, that the instantaneous axis of rotation does not strictly coincide with the principal axis of inertia. Though the angular difference between them must always have been small, we can, without having recourse to any extramundane influence, recognise two causes which, whether or not they may suffice to produce any change in the position of the main axis of inertia, undoubtedly tend to do so. In the first place, a widespread upheaval or depression of certain unsymmetrically arranged portions of the surface to a considerable amount would tend to shift that axis. In the second place, an analogous result might arise from the denudation of continental masses of land, and the consequent filling up of sea-basins. Lord Kelvin freely concedes the physical possibility of such changes. "We may not merely admit," he says, "but assert as highly probable, that the axis of maximum inertia and axis of rotation, always very near one another, may have been in ancient times very far from their present geographical position, and may have gradually shifted through 10, 20, 30, 40, or more degrees, without at any time any perceptible sudden disturbance of either land or water."[2] But though, in the earlier ages of the planet's history, stupendous deformations may have occurred, and the axis of rotation may have often shifted, it is only the alterations which can possibly have occurred during the accumulation of the stratified

[1] Professor Förster, *Rep. Brit. Assoc.* 1894, pp. 476-480, "On the Displacements of the Rotational Axis of the Earth." He gives a diagram of the path described on the earth's surface by the north pole. Professor Chandler had shown in 1891 that the rotational axis makes a complete circuit around the axis of figure in about 428 days instead of in about 305, as previously believed (*Astron. Journ.* No. 248, 1891). See also his observations in *Nature*, lvi. (1897), p. 40. More recently Professor Albrecht has published the results of an examination of all the observations from the beginning of 1890 to the middle of 1897 (*Astron. Nach.* No. 3619). A brief summary of his paper, with a diagram of the remarkably erratic movements of the north pole during the period, will be found in *Nature*, lviii. (1898), p. 42. More recently Dr. J. Halm has come to the conclusion that the changes in the position of the earth's axis of rotation are intimately connected with the varying display of forces on the surface of the sun, *Nature*, lxii. (1900), p. 460.

[2] *Brit. Assoc. Rep.* (1876), Sections, p. 11.

rocks, that need to be taken into account in connection with the evidence of changes of climate during geological history.

On the assumption, based on so many kinds of evidence, that the earth on the whole is practically an extremely rigid body, it is difficult to conceive of any alteration in its interior which could now so seriously disturb the position of its axis as to produce any important geological changes. Lord Kelvin, for instance, has estimated "that an elevation of 600 feet, over a tract of the earth's surface 1000 miles square and 10 miles in thickness, would only alter the position of the principal axis by one-third of a second, or 34 feet."[1] Then, as regards the effects of denudation, it has been calculated that if the whole high plateau of Central Asia together with the Himalaya mountains were worn down by the sub-aerial denuding agents and deposited in the Indian Ocean under the equator, the pole of the axis of inertia would only be shifted some 30 kilometres southward along the central meridian of the plateau.[2]

Professor George Darwin has shown that, on the supposition of the earth's complete rigidity, no redistribution of matter in new continents could ever shift the pole from its primitive position more than 3°, but that, if its degree of rigidity is consistent with a periodical readjustment to a new form of equilibrium, the pole may have wandered some 10° or 15° from its primitive position, or have made a smaller excursion and returned to near its old place. In order, however, that these maximum effects should be produced, it would be necessary that each elevated area should have an area of depression corresponding in size and diametrically opposite to it, that they should lie on the same complete meridian, and that they should both be situated in lat. 45°. With all these coincident favourable circumstances, an effective elevation of $\frac{1}{300}$th of the earth's surface to the extent of 10,000 feet would shift the pole $11\frac{1}{3}'$; a similar elevation of $\frac{1}{20}$th would move it $1° 46\frac{1}{2}'$; of $\frac{1}{10}$th, $3° 17'$; and of $\frac{1}{2}$, $8° 4\frac{1}{2}'$. Mr. Darwin admits these to be superior limits to what is possible, and that, on the supposition of intumescence or contraction under the regions in question, the deflection of the pole might be reduced to a quite insignificant amount.[3]

Under the most favourable conditions, therefore, on the assumption of the earth's high rigidity, the possible amount of deviation of the pole from its first position would appear to have been too small to have seriously influenced the climates of the globe within geological history. If we grant that these changes were cumulative, and that the superior limit of deflection was reached only after a long series of concurrent elevations and depressions, we must suppose that no movements took place elsewhere to counteract the effect of those about lat. 45° in the two hemispheres. But this is hardly credible. A glance at a geographical globe suffices to show how large a mass of land exists now both to the

[1] *Trans. Geol. Soc. Glasgow*, iv. p. 313. The situation of the supposed area of upheaval on the earth's surface is not stated.

[2] Professor Schiaparelli, 'Sur la rotation de la terre sous l'influence des actions géologiques,' St. Petersburg, 1889, p. 12.

[3] *Phil. Trans.* Nov. 1876.

north and south of that latitude, especially in the northern hemisphere, and that the deepest parts of the ocean are not antipodal to the greatest heights of the land. These features of the earth's surface are of old standing. There seems, indeed, to be no geological evidence in favour of any such geographical changes as could have produced even the comparatively small displacement of the axis considered possible by Professor Darwin.

If, however, it should eventually be found that a greater degree of plasticity of the material in the earth's interior may be conceded than at present seems to be probable, much more serious shiftings of the axis may be thus explained. As remarked by Major-General K. von Orff, "the movements of the pole assume a wholly different character if we ascribe a greater plasticity to the earth, or if we assume the possibility of a sudden and complete adjustment of the mass of the earth to the rotation-pole—a condition to which the planet might perhaps have approached in prehistoric times. On this assumption, great movements of the pole in relatively short periods are not excluded, and the hypotheses which many geologists have adduced in explanation of certain palæontological facts by greater changes in the position of the axis of rotation of the earth would thus obtain a mechanical confirmation."[1] The geological changes here referred to will be discussed in later portions of this text-book.

Geologists who have pondered over the abundance of the traces of present or former volcanic action distributed over the surface of the globe, over the evidence from the compressed strata in mountain regions that the crust of the earth must have a capacity for slipping towards certain lines, over the great amount of horizontal compression of strata which can be proved to have been accomplished, and above all, over the secular changes of climate, notably the existence of former warm climates near the north pole, have anxiously sought for some solution of these most difficult problems. When they were compelled by the arguments from physics to abandon their early conception of a thin crust over a liquid interior, the idea was suggested to them that their difficulties might be removed by the hypothesis that underneath the crust lies a fluid substratum over a rigid nucleus, and that, under these circumstances, changes in latitude would result from unequal thickening of the crust.[2] An ingenious suggestion was made by Sir John Evans that, even without any sensible change in the position of the axis of rotation of the nucleus of the globe, there might be very considerable changes of latitude due to disturbance of the equilibrium of the outer portion or shell by the upheaval or removal of masses of land between the equator and the poles, and to the consequent sliding of the shell over the nucleus until the equilibrium was restored.[3] Subsequently he precisely formulated his hypothesis as a

[1] "Ueber die Hülfsmittel, Methoden und Resultate der Internationalen Erdmessung," *Festrede, Akad. Wissensch. Munich*, 1899, p. 53; Schiaparelli, *op. cit.*

[2] Rev. O. Fisher, *Geol. Mag.* 1878, p. 552; 'Physics of the Earth's Crust,' 2nd edit. 1889, chap. xi.

[3] *Proc. Roy. Soc.* xv. (1867), p. 46.

question to be determined mathematically;[1] and the solution of the problem was worked out by the Rev. J. F. Twisden, who arrived at the conclusion that even the large amount of geographical change postulated by Sir J. Evans could only displace the earth's axis of figure to the extent of less than 10′ of angle, that a displacement of as much as 10° or 15° could be effected only if the heights and depths of the areas elevated and depressed exceeded by many times the heights of the highest mountains, that under no circumstances could a displacement of 20° be effected by a transfer of matter of less amount than about a sixth part of the whole equatorial bulge, and that even this extreme amount would not necessarily alter the position of the axis of figure.[2]

§ 6. **Changes of the Earth's Centre of Gravity.**—If the centre of gravity in our planet, as pointed out by Herschel, be not coincident with the centre of figure, but lie somewhat to the south of it, any variation in its position will affect the ocean, which of course adjusts itself in relation to the earth's centre of gravity. How far any redistribution of the matter within the earth, in such a way as to affect the present equilibrium, is now possible, we cannot tell. But certain revolutions at the surface may from time to time produce changes of this kind. The accumulation of ice round the pole, particularly during a glacial period, will displace the centre of gravity, and, as the result of this change, will raise the level of the ocean in the glacial hemisphere.[3] The late Dr. Croll estimated that, if the present mass of ice in the southern hemisphere is taken at 1000 feet thick extending down to lat. 60°, the transference of this mass to the northern hemisphere would raise the level of the sea 80 feet at the north pole. Other methods of calculation give different results. Mr. Heath put the rise at 128 feet; Archdeacon Pratt made it more; while the Rev. O. Fisher gave it at 409 feet.[4] Subsequently, in returning to this question, Croll remarked "that the removal of two miles of ice from the Antarctic continent [and at present the mass of ice there is probably thicker than that] would displace the centre of gravity 190 feet, and the formation of a mass of ice equal to the one-half of this, on the Arctic regions, would carry the centre of gravity 95 feet farther; giving in all a total displacement of 285 feet, thus producing a rise of level at the north pole of 285 feet, and in the latitude of Edinburgh of 234 feet." A very considerable additional displacement would arise from the increment of water to the mass of the ocean by the melting of the ice. Supposing half of the two miles of Antarctic ice to be replaced by an ice-cap of similar extent and one mile thick in the northern hemisphere, the other half being melted

[1] *Q. J. G. S.* xxxii. (1876), p. 62.

[2] *Q. J. Geol. Soc.* xxxiv. (1878), p. 41. See also E. Hill, *Geol. Mag.* v. (2nd ser.), pp. 262, 479. O. Fisher, *op. cit.*, pp. 291, 551. The question of the internal condition of the globe is discussed at p. 65.

[3] Adhemar, 'Révolutions de la Mer,' 1840.

[4] Croll, in *Reader* for 2nd September 1865, and *Phil. Mag.* April 1866; Heath, *Phil. Mag.* April 1869; Pratt, *Phil. Mag.* March 1866; Fisher, *Reader*, 10th February 1866.

into water and increasing the mass of the ocean, Dr. Croll estimated that from this source an extra rise of 200 feet would take place in the general ocean level, so that there would be a rise of 485 feet at the north pole, and 434 feet in the latitude of Edinburgh.[1] An intermittent submergence and emergence of the low polar lands might be due to such an alternate shifting of the centre of gravity.

To what extent this cause has actually come into operation in past time cannot at present be determined. It has been suggested that the "raised beaches," shore-lines (*strand-linien*), or old sea-terraces, so numerous at various heights in the north-west of Europe, might be due to the transference of the oceanic waters, and not to any subterranean movement, as generally believed. Had they been due to such a general cause, they ought to have shown evidence of a gradual and uniform decline in elevation from north to south, with only such local variations as might be accounted for by the influence of masses of high land or other local cause. No such feature, however, has been satisfactorily established.[2] On the contrary, the levels of the terraces vary within comparatively short distances, in such a manner as to indicate actual deformation of the surface of the solid earth. Though numerous on both sides of the mainland of Scotland, they disappear among the Orkney and Shetland islands, and yet these localities were admirably adapted for their formation and preservation.[3] The conclusion may be drawn that the "raised beaches" cannot be adduced as evidence of changes of the earth's centre of gravity, but are due to local and irregularly acting causes. (See Book III. Part I. Sect. iii. § 1, where this subject is more fully discussed.)

§ 7. **Results of the Attractive Influence of Sun and Moon on the Geological Condition of the Earth.**—Many speculations have been offered to account for a supposed former greater intensity of geological activity on the surface of the globe. Two causes for such greater intensity have been adduced. In the first place, if the earth has cooled down from an original molten condition, it has lost, in cooling, a vast amount of potential geological energy. It does not necessarily follow, however, that the geological phenomena resulting from internal temperature have, during the time recorded in the accessible part of the earth's crust, been steadily decreasing in magnitude. We might, on the contrary, contend that the increased resistance of a thickening cooled crust may rather have hitherto intensified the manifestations of subterranean activity, by augmenting the resistance to be overcome. In the second place, the earth may have been once more powerfully affected by external causes, such as the greater heat of the sun, and the greater proximity of the moon. That the formerly larger amount of solar heat received by the surface of our planet must have produced warmer climates and more rapid evaporation, with greater rainfall and the important chain of

[1] Croll, *Geol. Mag.*, new series, i. (1874), p. 347; 'Climate and Time,' chaps. xxiii. and xxiv. and *postea*, p. 286. Consult also Fisher, *Phil. Mag.* xxxiv. (October 1892), p. 337.

[2] The student ought, however, to consult Professor Suess' 'Antlitz der Erde' (or the French version, 'Face de la Terre'), for the arguments in favour of the opinion that the terraces do not involve any proof of change of level of the land.

[3] *Nature*, xvi. (1877), p. 415.

geological changes which such an increase would introduce, appears in every way probable, though the geologist has not yet been able to observe any indisputable indication of such a former intensity of superficial changes.

Professor Darwin, in investigating the bodily tides of viscous spheroids, has brought forward some remarkable results bearing on the question of the possibility that geological operations, both internal and superficial, may have been once greatly more gigantic and rapid than they are now.[1] He assumes the earth to be a homogeneous spheroid and to have possessed a certain small viscosity,[2] and he calculates the internal tidal friction in such a mass exposed to the attraction of moon and sun, and the consequences which these bodily tides have produced. He finds that the length of our day and month has greatly increased, that the moon's distance has likewise augmented, that the obliquity of the ecliptic has diminished, that a large amount of hypogene heat has been generated by the internal tidal friction, and that these changes may all have transpired within comparatively so short a period (57,000,000 years) as to place them quite probably within the limits of ordinary geological history. According to his estimate, 46,300,000 years ago the length of the sidereal day was fifteen and a half hours; the moon's distance in mean radii of the earth was 46·8 as compared with 60·4 at the present time. But 56,810,000 years back, the length of a day was only $6\frac{3}{4}$ hours, or about a quarter of its present value, the moon's distance was only nine earth's radii, while the lunar month lasted not more than about a day and a half (1·58), or $\frac{1}{17}$th of its present duration. He arrives at the deduction that the energy lost by internal tidal friction in the earth's mass is converted into heat at such a rate that the amount lost during 57,000,000 years, if it were all applied at once, and if the earth had the specific heat of iron, would raise the temperature of the whole planet's mass 1,760° Fahrenheit, but that the distribution of this heat-generation has been such as not to interfere with the normal augmentation of temperature downward due to secular cooling, and the conclusion drawn therefrom by Lord Kelvin. Mr. Darwin further concludes from his hypothesis that the ellipticity of the earth's figure having been continually diminishing, "the polar regions must have been ever rising and the equatorial ones falling, though, as the ocean followed these changes, they might quite well have left no geological traces. The tides must have been very much more frequent and larger, and accordingly the rate of oceanic denudation much accelerated. The more rapid alternation of day and night[3] would probably lead to more sudden and violent storms,

[1] *Phil. Trans.* 1879, parts i. and ii.

[2] The degree of viscosity assumed is such that "thirteen and a half tons to the square inch acting for twenty-four hours on a slab an inch thick displaces the upper surface relatively to the lower through one-tenth of an inch. It is obvious," says Mr. Darwin, "that such a substance as this would be called a solid in ordinary parlance, and in the tidal problem this must be regarded as a very small viscosity." *Op. cit.* p. 581.

[3] According to his calculation, the year 57,000,000 of years ago contained 1800 days instead of 365.

and the increased rotation of the earth would augment the violence of the trade-winds, which in their turn would affect oceanic currents."[1] As above stated, no facts yet revealed by the geological record compel the admission of more violent superficial action in former times than now. But though the facts do not of themselves lead to such an admission, it is proper to inquire whether any of them are hostile to it. It will be shown in Book VI. that even as far back as early Palæozoic times, that is, as far into the past as the history of organised life can be traced, sedimentation took place very much as it does now. Sheets of fine mud and silt were pitted with rain-drops, ribbed with ripple-marks, and furrowed by crawling worms, exactly as they now are on the shores of any modern estuary. These surfaces were quietly buried under succeeding sediment of a similar kind, and this for hundreds and thousands of feet. Nothing indicates violence; all the evidence favours tranquil deposit.[2] If, therefore, Mr. Darwin's hypothesis be accepted, we must conclude either that it does not necessarily involve such violent superficial operations as he supposes, or that even the oldest sedimentary formations do not date back to a time when the influence of increased rotation could make itself evident in sedimentation, that is to say, on Mr. Darwin's hypothesis, the most ancient fossiliferous rocks cannot be as much as 57,000,000 years old.

§ 8. **Geological Condition of the Moon.**—In the foregoing pages notice has been taken of some of the relations between the earth and its satellite, and further reference may here be made to certain aspects of the moon which bear on the geological history of our planet. The inference seems natural that the moon and earth formed originally parts of one heavenly body. Professor George Darwin believes that when this body was rotating so fast as to make one rotation in five hours, the influence of the powerful tides induced in its mass by the sun may have actually ruptured the planet, and that in this way the moon may have been suddenly thrown off.[3] Dr. Osmond Fisher[4] has suggested that possibly the great hollow of the Pacific Ocean may mark the scar left by the discharge of our satellite. It has been also conjectured that the moon resulted from the rupture of a planetary ring of meteorites, which by collision became a united mass of gaseous or liquid substance.

The moon is computed to have a diameter of 2153 miles (3464 kilometres) and a volume about one forty-ninth of that of the earth. Its mean distance from us is 238,793 miles (384,000 kilometres). As already

[1] *Op. cit.* p. 532.

[2] Sir R. Ball (*Nature*, xxv. 1881, pp. 79, 103), starting from Professor Darwin's data, pushed his conclusions to such an extreme as to call in the agency of tides more than 600 feet high in early geological times. In repudiating this application of his results, Mr. Darwin (*Nature*, xxv. p. 213) employs the argument I have here used from the absence of any evidence of such tidal action in the geological formations, and from the indication, on the contrary, of tranquil deposit.

[3] *Phil. Trans.* 1879, part ii., "The Precession of a Viscous Spheroid and the Remote History of the Earth."

[4] 'Physics of the Earth's Crust,' 2nd edit. p. 338.

stated, it is composed of materials lighter than those of our planet, its density being little more than half that of the earth, or about three times that of water. No certain trace of an atmosphere has been detected on the moon, nor any indication of the presence of water. Hence the epigene changes which play so important a part on the surface of the earth must be hardly perceptible on the moon. Perhaps the only effects of that class which are produced arise from the strain induced by the enormous differences of temperature between day and night. In full sunshine the bare rocks must be heated beyond any temperature experienced even in the driest tropical climates on the earth, and at night must be rapidly cooled down towards the temperature of space. Such a strain on the cohesion of the rocks may possibly induce rapid disintegration, though it must be admitted that no undoubted evidence of this decay has been observed on the moon's surface.

But if the epigene agents are absent, those of the hypogene kind appear to have been at one time extraordinarily active on the moon. What are called "craters," from their resemblance to the cavities of terrestrial volcanoes, have long been known to be scattered abundantly over the moon's surface. They are of all sizes, from such as can only be faintly discerned with the most powerful telescopes, up to vast caldron-shaped abysses with walls 8000 to 15,000 feet high. It is computed that the total number of visible lunar craters of all dimensions amounts to from 20,000 to 30,000. There does not appear to be any area on the surface of the globe where a similar profusion of craters can be seen. Not only are the lunar examples far more numerous than the terrestrial, but they far surpass in dimensions even the most colossal of those on the earth. Various theories have been proposed to account for the characteristic features on the moon's surface. One of these explanations supposes that when the main mass of the moon was liquid and surrounded with a thin crust, its rotation, then more rapid than now, gave rise to tides by which the crust was rent open so as to allow some of the liquid of the interior to flow out at the surface and then subside again. As the exuded material congealed at its edges, its boundary was marked by a rim of hardened rock, which was increased by the upwelling caused by subsequent tides, and thus circular crater-walls were formed around a solid lava plain in the centre.[1] Another view, held by the majority of writers, regards the craters as truly relics of lunar volcanoes testifying to a volcanic activity immensely more energetic than anything with which we are acquainted in the past history or present condition of the earth. That some of the rocky material of the moon is akin to well-known terrestrial lavas was inferred by M. Landerer, who found that their polarisation angles coincided with those given by obsidian and vitrophyre.[2] Professor Suess, after a comparison of the lunar surface with the phenomena of terrestrial vulcanism and the behaviour of large masses of molten material such as are seen at iron-furnaces and glass-works, arranged the evidence furnished by the moon in the following manner. 1st Phase,

[1] Faye, *Rev. Sci.* xxvii. (1881), p. 130; H. Ebert, *Ann. Phys. Chem.* xli. (1890), p. 351.
[2] *Compt. rend.* cxi. (1890), p. 210.

the melting of great plains (Mare Serenitatis; not visible on the earth). 2nd Phase, *a*, melting without uplift of the surface (Batholiths; granite of Erzgebirge, not recognisable on the moon), *b*, melting of craters of small diameter and quiet up-welling of the lava (Hawaii, Ptolemaeus, Wargentin). 3rd, formation of fissures with rhapsodical explosions (Laki in Iceland, Vesuvius, Maare of the Eifel, Crater-rills, Hyginus). As local consequences of eruptions come the phases of fumaroles, which are observed on the earth in 2*b* and 3, but have not been recognised on the moon.[1] No satisfactory proof has yet been obtained of any present volcanic activity in the moon or of other definite changes of its surface. At the same time certain discrepancies have been observed between some of the older and later maps of lunar topography which may not be wholly due to erroneous or imperfect delineation, but may possibly in the end be discovered to indicate actual volcanic changes.[2]

A third class of opinions regarding the lunar "craters" holds them to be most probably due, not to any action within the moon, but to the impact of solid bodies from without. This view has been especially developed by Mr. G. K. Gilbert, who, after studying the moon's surface in 1892 with the 26½-inch refractor of the United States Naval Observatory, came to the conclusion that the phenomena become more intelligible if we suppose that before the moon came into existence the earth was surrounded with a ring of meteoritic bodies similar to those that constitute Saturn's ring; that the small bodies in this terrestrial ring eventually coalesced, gathering first around a large number of nuclei and finally all uniting in a single sphere, the moon. The lunar craters are thus taken to be the scars produced by the collision of those minor aggregations or moonlets, which last surrendered their individuality. There can be no doubt that the collision of bodies moving with planetary velocities may generate heat enough not merely to melt them, but to reduce them to the gaseous condition. It has been computed by Mr. R. S. Woodward that a body falling from an infinite distance to the moon's surface merely under the influence of the attraction of the satellite itself will acquire a velocity of one mile and a half per second, which would more than suffice to fuse the body. But the velocity of shooting stars is as much as 45 miles in a second, and if any such swiftly moving mass were to fall on the moon it would not only be melted itself, but a considerable tract of the rock-mass by which its motion was arrested would also be liquefied. Mr. Gilbert believes that in this way not only may the crater topography of the moon's surface be most satisfactorily explained, but that a number of other features ordinarily obscure may be accounted for, such as the furrows, rills, rill-pits, and white streaks.[3]

[1] E. Suess, "Einige Bemerkungen über den Mond," *Sitz. Akad. Wiss.*, Vienna, *Math. Phys.* civ. (1895).

[2] Pickering, *Nature*, xlvi. (1892), p. 134; xlvii. p. 7. On the absence of an atmosphere in the moon, see G. H. Bryan, "The Moon's Atmosphere and the Kinetic Theory of Gases," *Brit. Assoc.* 1893, pp. 682-685; F. F. Grensted, *Proc. Liverpool Geol. Soc.* Nov. 1887.

[3] G. K. Gilbert, "The Moon's Face," *Bull. Philosoph. Soc. Washington*, vol. xii. (1893), pp. 241-292.

# BOOK II.

## GEOGNOSY.

### AN INVESTIGATION OF THE MATERIALS OF THE EARTH'S SUBSTANCE.

### PART I.—A GENERAL DESCRIPTION OF THE PARTS OF THE EARTH.

A DISCUSSION of the geological changes which our planet has undergone ought to be preceded by a study of the materials of which the planet consists. This latter branch of inquiry is termed Geognosy.

Viewed in a broad way, the earth may be considered as consisting of (1) two envelopes,—an outer one of gas (atmosphere), completely surrounding the planet, and an inner one of water (hydrosphere), covering about three-fourths of the globe; and (2) a globe (lithosphere), cool and solid on its surface, but possessing a high internal temperature.

#### I.—*The Envelopes—Atmosphere and Hydrosphere.*

It is certain that the present gaseous and liquid envelopes of the planet form only a portion of the original mass of gas and water with which the globe was invested. Fully a half of the outer shell or crust of the earth consists of oxygen, which probably once existed in the primeval atmosphere. The extent, likewise, to which water has been abstracted by minerals is almost incredible. It has been estimated that already one-third of the whole mass of the ocean has been thus absorbed. Eventually the condition of the planet will probably resemble that of the moon—a globe without air, or water, or life of any kind.

1. **The Atmosphere.**—The gaseous envelope to which the name of atmosphere is given extends from the earth's surface to a distance which has been variously estimated, according to the methods of observation employed.[1] From the phenomena of twilight it may be inferred that

[1] Laplace considered that the atmosphere has a volume about 155 times that of the rest of the earth, and is arranged lenticularly, so that its polar diameter is about 4·4 times and its equatorial diameter about 6·6 times the polar and equatorial diameters of the earth. Hence,

the atmosphere must be at least 45 miles thick. The aurora indicates a sensible atmosphere at 100 miles, and clouds have been detected at heights of nearly 100 miles. Meteorites, which become incandescent by friction against our atmosphere, sometimes appear at heights of 150 miles. We may therefore infer that the atmosphere stretches for at least that distance from the earth's surface, and probably in a state of extreme tenuity much farther.[1] At sea-level the atmosphere presses on the earth's surface with a weight equal to that of a layer of mercury 30 inches deep, or of a sheet of water 34 feet deep. Every square inch of that surface thus supports a pressure of 14¾ pounds. But the pressure rapidly diminishes with height above the sea. At a height of 18,500 feet it sinks to only one-half, and in balloon ascents it has been found at twice that height (or seven miles) to have diminished to one-fourth.

Many speculations have been made regarding the chemical composition of the atmosphere during former geological periods. There can indeed be no doubt that it must originally have differed very greatly from its present condition. It has been contended, for instance, that originally there was little or no free oxygen in the atmosphere, which may have consisted mainly of nitrogen, carbonic acid, and aqueous vapour.[2]

Besides the abstraction of the oxygen which now forms fully a half of the outer crust of the earth, the vast beds of coal found all over the world, in geological formations of many different ages, doubtless represent so much carbon-dioxide (carbonic acid) once present in the air. According to Sterry Hunt, the amount of carbonic acid absorbed in the process of rock-decay, and now represented in the form of carbonates, especially limestones, in the earth's crust, probably equals two hundred times the present volume of the entire atmosphere.[3]

according to this view, it must be some 17,000 miles in depth at the poles and about 26,000 miles at the equator. Some recent researches regarding the height and mass of the atmosphere by Mascart are given in *Compt. rend.* cxiv. (1892), p. 93 ; see also S. Arrhenius, *Öfvers. Akad. Stockholm*, 1900, p. 545 ; Eckholm, *op. cit.* 1901, p. 619.

[1] The Rev. W. F. Denning states, as the result of his considerable experience, that about 20 per cent of meteors are at least 100 miles high at the instant of their becoming visible, that the distance is rarely as much as 150 miles, and seldom reaches beyond 130 miles—*Nature*, lvii. (1898), p. 541.

[2] Professor C. J. Koene, as quoted by Dr. T. L. Phipson in *Chemical News* for 1893 and 1894. Lord Kelvin has speculated on the absence of oxygen from the primitive atmosphere, the presence of this gas now in the air being probably due to the action of sunlight on plants (*Nature*, lvi. 1897, p. 461). In a paper published in 1900 (*Phil. Mag.* 5th ser. vol. l. pp. 312, 399) Mr. J. Stevenson concludes that there was probably a time, and possibly a long time, when there was no free oxygen in our atmosphere, and that "our present supply of free oxygen has been all produced by the action of sunlight on vegetation."

[3] *Brit. Assoc. Rep.* 1878, Sects. p. 544. This and cognate subjects connected with the carbonic acid in the atmosphere and the earth's crust are discussed by Professor Chamberlin in a paper on "The Influence of Great Epochs of Limestone-formation upon the Constitution of the Atmosphere," *Journ. Geol.* vi. (1898), pp. 609-621. See also Professor Högbom as quoted by Dr. Arrhenius in *Phil. Mag.* 1896, p. 269.

Any addition to the existing proportion of carbon-dioxide in the atmosphere would have an important effect on climate, seeing that this gas possesses so marked a capacity for absorbing heat. Professor Arrhenius has estimated if the present proportion of the gas in the atmosphere were increased two and a half or three times, the effect would be to raise the temperature of the Arctic regions about 8° to 9° C., and thus to bring back such a genial climate as those lands possessed in Tertiary time.[1] It has often been contended that, during the Carboniferous period, the atmosphere must have been warmer and with more aqueous vapour and carbon-dioxide in its composition than at the present day, to admit of so luxuriant a flora as that from which the coal-seams were formed.

As now existing, the atmosphere is considered to be normally a mechanical mixture of nearly 4 volumes of nitrogen and 1 of oxygen (N79·4, O20·6), with minute proportions of carbon-dioxide and water-vapour and still smaller quantities of ammonia and the powerful oxidising agent, ozone. These quantities are liable to some variation according to locality. The mean proportion of carbon-dioxide is about 3·5 parts in every 10,000 of air. In the air of streets and houses the proportion of oxygen diminishes, while that of carbon-dioxide increases. According to the researches of Angus Smith, very pure air should contain not less than 20·99 per cent of oxygen, with 0·030 of carbon-dioxide; but he found impure air in Manchester to have only 20·21 of oxygen, while the proportion of carbon-dioxide in that city during fog was ascertained to rise sometimes to 0·0679, and in the pit of the theatre to the very large amount of 0·2734. As plants absorb carbon-dioxide in the day and give it off at night, the quantity of this gas in the atmosphere oscillates between a maximum at night and a minimum in the day. During the part of the year when vegetation is active, it is believed that there is at least 10 per cent more carbonic acid in the air of the open country at night than in the day.[2] Small as the normal percentage of this gas in the air may seem, yet the total amount of it in the whole atmosphere probably exceeds what would be disengaged if all the vegetable and animal matter on the earth's surface were burnt.

The other substances in the air are gases, vapours, and solid particles. In recent years the researches more particularly of Lord Rayleigh and Professor William Ramsay have led to the detection of a number of previously unknown gases present in minute quantities in the atmosphere. Of these gases the most important is that to which the name of Argon has been given; others are Neon, Helium, Krypton, and Xenon. The proportions of these gases in air are thus stated by Professor Ramsay.

[1] S. Arrhenius, *Bihang K. Vet. Akad. Stockholm*, xxii. (1896), No. 1; *Phil. Mag.* 1896, pp. 237-276; *Öfvers. K. Vet. Akad. Stockholm*, 1901, No. 1, pp. 25-58. But see also K. Angström, *op. cit.* 1901, pp. 371-389; Professor Chamberlin, *Journ. Geol.* v. (1897), pp. 663-683; vii. (1899), pp. 545-584.

[2] Professor G. F. Armstrong, *Proc. Roy. Soc.* xxx. (1880), p. 343.

Air contains 0·937 part of Argon per hundred.
„ one or two parts of Neon per hundred thousand.
„ one or two parts of Helium per million.
„ about one part of Krypton per million.
„ about one part of Xenon per twenty million.[1]

Of much more consequence than these minute proportions of gases is the percentage of aqueous vapour which, always present in the air, varies in amount according to temperature.[2] It is by this vapour, together with the carbon-dioxide and suspended dust-particles, that the radiant heat in the atmosphere is absorbed.[3] The water-vapour condenses into dew, rain, hail, and snow, and is thus of paramount importance in the great series of epigene processes which play so large a part in the geological changes of the earth's surface (Book III. Part II.). In assuming one of its visible forms and descending through the atmosphere, the previously dissolved and invisible vapour takes up a minute quantity of air, and of the different substances which the air may contain. Being caught by the rain, snow, hail, or dew, and held in solution or suspension, these substances can be best examined by analysing rain-water or melted snow and hail. In this way, the atmospheric gases, together with ammonia, nitric, sulphurous, and sulphuric acids, chlorides, various salts, solid carbon, inorganic dust, and organic matter have been detected. The fine microscopic dust so abundant in the air is no doubt for the most part due to the action of wind in lifting up the finer particles of disintegrated rock on the surface of the land. Volcanic explosions sometimes supply prodigious quantities of fine dust. There is probably also some addition to the solid particles in the atmosphere from the explosion and dissipation of meteorites on entering our atmosphere. To the wide diffusion of minute solid particles in the air great importance in the condensation of vapour is now assigned.[4] (Book III. Part II. Sect. ii.)

The comparatively small, but by no means unimportant, proportions of these minor components of the atmosphere are much more liable to variation than those of the more essential gases. Chloride of sodium, for instance, is, as might be expected, particularly abundant in the air bordering the sea. Nitric acid, ammonia, and sulphuric acid appear most conspicuously in the air of towns. The organic substances present in the air are sometimes living germs, such as probably often lead to the

[1] 'The Gases of the Atmosphere,' London, 1896, p. 240; *Nature*, lxv. (1901), p. 164.

[2] A cubic metre of air at the freezing-point can hold only 4·871 grammes of water-vapour, but at 40° C. can take up 50·70 grammes. One cubic mile of air saturated with vapour at 35° C. will, if cooled to 0°, deposit upwards of 140,000 tons of water as rain. Roscoe and Schorlemmer's 'Chemistry,' i. p. 452.

[3] Tyndall pointed out this important function of the aqueous vapour of the atmosphere. S. A. Hill, *Proc. Roy. Soc.* xxxiii. pp. 216, 435. See also Arrhenius, *Öfvers. Vet. Akad. Stockholm*, 1901, p. 54.

[4] On the dust in the air, see Mr. J. Aitken's papers in the *Proc. Roy. Soc. Edin.*, particularly in the volume for 1891.

propagation of disease, and sometimes mere fine particles of dust derived from the bodies of living or dead organisms.[1]

As a geological agent, the atmosphere effects changes by the chemical reactions of its constituent gases and vapours, by its varying temperature, and by its motions. Its functions in these respects are described in Book III. Part II. Sect. i.

2. **The Oceans.**—Rather less than three-fourths of the surface of the globe (or about 144,712,000 square miles) are covered by the irregular sheet of water known as the Sea. Within the last twenty years, much new light has been thrown upon the depths, temperatures, and biological conditions of the ocean-basins, more particularly by the *Lightning*, *Porcupine*, *Challenger*, *Tuscarora*, *Blake*, *Gazelle*, and other expeditions fitted out by the British, American, German, Norwegian and Swedish Governments.[2] The ocean which up to the present time has been most extensively explored is the Atlantic. This important division of the hydrosphere runs as a long and winding belt of water between the New World and the Old. Towards the north it is closed in by a submarine ridge, which, extending from the north-west of Scotland through the Faroe Islands and Iceland to Greenland, separates it from the Arctic basin. Stretching from the Arctic to the Antarctic waters, the Atlantic Ocean crosses the various zones of temperature which girdle the globe. Its central parts lave the shores of equatorial America and Africa. North of these, it reaches the temperate climates of North

[1] The air of towns is peculiarly rich in impurities, especially in manufacturing districts, where much coal is used. These impurities, however, though sometimes of serious consequence from a sanitary point of view, do not sensibly affect the general atmosphere, seeing that they are probably in great measure taken out of the air by rain, even in the districts which produce them. They possess, nevertheless, a special geological significance and in this respect, too, have important economic bearings. See on this whole subject, Angus Smith's 'Air and Rain,' a valuable paper by Prof. W. N. Hartley and Mr. H. Ramage on "The Mineral Constituents of Dust and Soot from Various Sources" (*Proc. Roy. Soc.* 1901), and the account of Rain in Book III. Part II. Sect ii.

[2] See Wyville Thomson, 'The Depths of the Sea,' 1873; 'The Atlantic,' 1877; the voluminous *Report of Challenger Expedition*, especially the two "Narrative" volumes, giving a summary of results; A. Agassiz, 'Three Cruises of the *Blake*,' 1888; *Die Forschungsreise S.M.S. Gazelle*, Berlin, 1889, 1900; *Den Norske Nordhavs-Expedition*, 1876-78, in seven large volumes in Norwegian and English, the last of which was issued in 1901; *The Norwegian North Polar Expedition*, edited by Fridtjof Nansen, 1893-96, of which three volumes have been published. The results of Swedish hydrographical research, 1896-99, are summarised in *Bihang Vet. Akad. Handling*, Stockholm, xxv. ii. (1900), p. 1, with an English synopsis and numerous maps of North Sea. Besides these more compendious works, an extensive literature has grown up in recent years on the subject of oceanography. Numerous papers will be found in the journals of the different Geographical Societies, and various separate treatises have been devoted to the subject, such as Thoulet's 'Oceanographie,' 2 vols., Paris, 1890-96; Boguslawski und Krümmel, 'Handbuch der Ozeanographie,' Stuttgart, 1884-87; Krümmel's 'Der Ozean,' Leipzig, 1886; J. Walther's 'Allgemeine Meereskunde,' Leipzig, 1893. Copious references to the literature of the subject will be found in Professor Supan's 'Grundzüge der Physischen Erdkunde,' Leipzig, 1896; and still more in Professor Günther's 'Handbuch der Geophysik,' ii., Stuttgart, 1899.

America and Europe. At the southern end it enters the icy Polar regions.[1]

A further feature of geological importance is seen in the fact that, owing to the arrangement of the continents which bound it on the west and east, the Atlantic receives a far larger river-drainage than any other ocean. The map shows that down the whole length of America all the large rivers flow eastward, and therefore fall into the Atlantic—the St. Lawrence, Mississippi, Orinoco, Amazon, and La Plata. In Europe and Africa, if we include the rivers which enter the Mediterranean and Black Sea, by far the largest proportion of the drainage finds its way into this ocean by such important rivers as the Rhine, Rhône, Danube, Dnieper, Nile, Niger, and Congo. The Atlantic basin is thus the great reservoir into which the largest rivers of the globe discharge their waters.

From the numerous soundings which have been taken throughout its entire length and breadth, the broad features of the floor of this ocean can be laid down with considerable accuracy upon a map. The wider parts of the Atlantic have a depth of from 2000 to 3000 fathoms, or from about 2 to 3½ miles. They form a vast undulating plain, crossed by a ridge, which may be regarded as starting from the western edge of the great plateau whereon Britain stands. Passing southwards by the Azores, that mark its position and highest elevation, it forms what is known as the Dolphin Rise, which, at its southern end, about latitude 30° N., ascends to within 400 fathoms from the surface. The ridge then strikes southwestward at a depth of less than 2000 fathoms to the coast of Guiana, whence it turns south-eastward across the ocean, coming to the surface under the equator in the lonely St. Paul's Rock, and turning southward as a long ridge from which the volcanic islets of Ascension and Tristan d'Acunha rise.

For a distance of some 230 miles to the west of the British Isles the slope of the Atlantic bottom is very gentle, being only six feet in the mile.[2] But beyond that limit the ground descends more rapidly, for in the next 20 miles there is a fall of 9000 feet, or a descent of 450 feet in the mile, down to the level of the great submarine plain, which stretches for hundreds of miles to the west, with little variety of surface. This plain ascends slowly towards the north till it forms the great plateau which, culminating in the Faroe Islands and Iceland, separates the deeper water of the Atlantic from that of the Arctic Ocean. The Newfoundland banks prolong the North American continental mass far into the ocean. The Florida peninsula and West Indian Islands separate the deep Atlantic waters from the basins of the Mexican Gulf and Caribbean Sea, which are obviously submerged enclosed seas.

The central submarine Atlantic ridge, and the deep hollow on either side of it, run in the same general curving line as the continental lands that form the eastern and western boundaries of this ocean. Both to the

[1] A. G., 'Elementary Lessons in Physical Geography,' p. 117.

[2] For the north-eastern part of the Atlantic, see an interesting paper by Mr. W. H. Hudleston, *Geol. Mag.* 1899, pp. 97, 145.

north and south of the equator, the floor of each of the winding troughs sinks here and there into profound abysses which have been found by soundings to be from 3000 to 4000 fathoms in depth. About 100 miles north from the Island of St. Thomas, the *Challenger* obtained a sounding of 3875 fathoms, or rather less than $4\frac{1}{2}$ miles, in what appears to be a vast hollow running north-eastwards from the end of the ridge on which the West Indian Islands rise. Subsequently a much deeper depression has been found near the Virgin Islands, about 70 miles north of Porto Rico, West Indies, where a sounding of 4561 fathoms or 27,366 feet was obtained. This is the greatest depth yet found in the Atlantic Ocean. It must of course be remembered that in proportion to the vast area of this ocean the soundings are relatively few in number and far apart. Where they have been made close together they have sometimes revealed greater inequalities of level than could have been suspected. Thus in 1883, while a series of soundings for telegraphic purposes was taken to the west of north-west Africa, in water previously supposed to be deep and possessing a tolerably uniform bottom, some submarine peaks were met with rising to within 50 fathoms of the surface.[1]

The general contour of the bottom of the Pacific Ocean is indicated by the distribution of the islands, and has been further elucidated by recent soundings. The bottom of this vast basin lies generally more than 2000 fathoms below the surface. But across its centre, between Japan and the coast of Chili, it is varied by a series of ridges separated by deep hollows which have a general trend from north-west to south-east. On these ridges numerous islands and archipelagoes rise to the surface and form the most characteristic feature of this ocean. The ridge which culminates in New Zealand runs at a right angle to the prevalent direction of the sub-oceanic ridges, but it is really a branch of one of these. We see that in the North Island the land turns round towards the north-west, and this direction is maintained by the continuation of the ridge under the sea. The New Hebrides, Solomon Islands, and New Guinea mark the unsubmerged peaks of another great ridge, which is prolonged westward by Celebes and Borneo, and sends a branch northward through the chain of the Philippine Islands. A strongly defined ridge strikes southward from Japan, and is marked at the surface by the Bonin and Marianne groups of islands. The Caroline, Marshall, Gilbert, Ellice, Fiji, Friendly, and Hervey Islands show the positions of other elevated portions of the ocean-floor. It is worthy of notice that while the large islands on the prolongation of the Asiatic and Australian plateau (New Caledonia, New Zealand, and others) are composed mainly of non-volcanic rocks, such as those of which the continents chiefly consist, the scattered oceanic islands, where they present any other material than coral-rock, reveal a volcanic orgin. They have probably been formed by the piling up of volcanic rocks from submarine eruptions. In the case of Hawaii the volcanic peaks rise 13,760 feet above the sea-level.

As in the Atlantic basin, the hollows between the ridges sink into deep troughs, some of which have been distinguished by special names

[1] *Times*, 7th Dec., 1883. [J. Y. Buchanan.]

generally taken from the names of the investigators or the vessels engaged in deep-sea research. Thus in the northern Pacific, between the chain of the Aleutian Islands and the great submarine bank from which the Sandwich Islands rise, a vast hollow stretches from the coast of Japan towards that of North America. This depression has been called the Tuscarora Deep, after the United States surveying ship of that name. It sinks westward along the east side of Japan into a long, narrow abysmal trough in which, in the year 1874, the *Tuscarora* took a sounding of 4655 fathoms or 27,930 feet. For some years this remained the deepest known abyss on the floor of any part of the ocean. The *Challenger* had already recorded a depth of 4475 fathoms in the Caroline Archipelago. But the British surveying ship *Penguin* has since obtained still deeper soundings to the south of the Tonga or Friendly Islands. In 1895, in lat. 23° 40′ S., long. 175° 10′ W., the sounding-tube had reached a depth of 4900 fathoms when, unfortunately, the wire broke. The investigation was resumed later by the same ship with success. In lat. 30° 28′ S., long. 176° 39′ W., a depth was obtained of no less than 5155 fathoms or 30,930 feet—the greatest depth anywhere yet known.[1] It will be seen from the map that this profound abyss lies to the south of the Kermadec Islands and about 300 miles north-east from the East Cape of New Zealand. It is a remarkable fact that the deepest parts of the oceans as revealed by actual soundings do not lie in or near the centres of their basins, but in every case have been met with not far from land. While the greatest depths have been observed between the Tonga Islands and New Zealand, profound abysses have been found close to the borders of the Pacific. Besides the Tuscarora Deep, parallel with the trend of Japan, another trough, upwards of 4000 fathoms deep, has been met with lying parallel with the giant chain of the Andes at a distance of only 50 miles from the coast of Peru.

Although the great water envelope of our planet may, for the sake of convenience, be parcelled out into separate oceans, these are all united into one vast continuous sheet of water. Here and there, however, owing to the way in which the land has been ridged up, portions of the water have been almost separated from the main mass. Of these Enclosed Seas, the best example is that which has long been known as the Mediterranean Sea. The Black and Baltic Seas in Europe, Hudson's Bay, the Caribbean Sea, and the Gulf of Mexico in North America, the Red Sea, Persian Gulf, and Seas of Japan and Okhotsk in Asia, are other illustrations. Some of the enclosed seas which are comparatively shallow really belong not to the oceanic but to the continental areas of the earth's surface. Though their sites are now occupied by the sea, they may once have been land, and might be raised into land again without greatly disturbing the present order of things.

Occasionally, by the uprise of its floor, portions of the ocean have been elevated and completely cut off from the main body of oceanic waters, so as to form Inland Seas, of which the Caspian Sea and Sea of Aral, and some of the great African Lakes, are important instances. The

[1] *Nature*, lii. (1895), p. 550 ; liii. (1896), p. 392.

Caspian Sea covers a larger space than the British Isles. Its surface is about 85 feet below sea-level, and its greatest depth amounts to nearly 3000 feet. Its waters are tenanted by seals and other animals that elsewhere inhabit the ocean. That a much larger area in that region was once submerged is shown by the fact that in the tracts of land which now enclose the Caspian and Sea of Aral and separate them from the Black Sea on the one hand, and from the Arctic Ocean on the other, beds of dead sea-shells are found. The main body of the ocean has been excluded by the rise of its bottom into land. The land along the coast of Siberia has in comparatively recent times been raised out of the sea, and there is some evidence to show that the Arctic Ocean formerly extended in a long arm between Europe and Asia as far as the hill-range which is now cut through by the narrow channel of the Bosphorus, but did not communicate with the present Mediterranean Sea, and that by the rise of the land towards the north all that part of this vast inlet lying to the south of the parallel of 50° or 52° N. was cut off from the main ocean. The present abundant salt lakes and marshes, as well as the two large basins of the Caspian and Aral, have been regarded as the mere shrunk remnants of this old Mediterranean Sea. The Black Sea has been separated from the waters of the Caspian region, and the intervening ridge between it and the Mediterranean Sea has been cut through, so that the Black Sea now communicates through the Bosphorus and Sea of Marmora with the Mediterranean. There seems also to be less rain or more evaporation now than formerly in the region of the Caspian and Aral, so that these sheets of water are still further shrinking.

In recent years the extraordinary fact has been brought to light that some of the great African lakes now filled with fresh water are probably portions of the sea-bottom which have been uplifted, for marine forms of life still survive in them. A vast line of depression (the Great Rift Valley) serves here to mark one of the greatest and most recent revolutions in the topography of the earth's surface. Further reference to Inland Seas and Lakes will be made in Book III. Part II. Sect. ii. § 4.

But not only have portions of the sea-bottom been uplifted and isolated into inland sheets of water; the land has in many places sunk under the sea, carrying down with it, uneffaced, its characteristic terrestrial features. Among these features some of the most recognisable are the lines of valley which were carved out on the surface of the land by subaerial denudation.[1] It will be pointed out in Book III. Part I. Sect. iii. § 1, that many glens are prolonged under the sea as sea-inlets or fjords, and that even far from the coast such traces of a former terrestrial surface may be recognised.

A question of high importance in geological inquiry is the form of the surface of the sea, or what is usually called the sea-level. It used to be generally assumed that this surface is stable and uniform and nearly that of an ellipsoid of revolution, owing its equilibrium to the force of gravity on the one hand and the centrifugal force of rotation on the other. But in recent years this conception has been called in question both by

[1] The floor of the North Sea is a notable illustration of such a submergence.

physicists and geologists. Observations as well as calculations have shown that the attraction exercised by masses of land raises the level of the adjacent sea, and attempts have been made to determine how far the deformation thus caused departs from the mean of the theoretical ellipsoid of revolution. According to Bruns a continent may cause a difference of more than 3000 feet between the actual level of the sea and that of the ellipsoid. But the results of such calculations will greatly depend on the assumption on which they start as to the nature of the earth's crust. R. S. Woodward has calculated that if the continent of Europe and Asia be supposed to be simply a superficial aggregation of matter with a density as great as the parts under the sea, the elevation of sea-level at the centre of the continent due to attraction would amount to about 2900 feet, but that, if the continental mass be assumed to imply a defect of density underneath it, the elevation of the sea at the centre of the continent due to attraction would be only about 10 feet.[1] The actual levellings carried out in Europe have shown, however, a much smaller variation from mean sea-level than might have been anticipated. Taking the mean surface of the Mediterranean at Marseilles as a datum-line, it has been found that the surface of that expanse of water is from 5 to 8 centimetres lower farther to the east, but the level at Trieste is 2 cm. higher. In the Atlantic the level is higher than at Marseilles, the greatest difference observed being at St. Jean de Luz, where the level is 15 cm. above that of Marseilles. Passing through the English Channel, where the surface is still rather above the normal, we find that it sinks in the North Sea, being as much as 16 cm. or rather more than six inches below the Marseilles datum at Ostend. Farther north at Cuxhaven the level rises to 3 cm. above datum, but in the Baltic it again sinks below it, being 9 cm. at Travemünde, 4 cm. at Warnemünde, and 2 cm. at Swinemünde.[2] It would thus appear that the extreme range of variation of sea-level round the coast-line of Europe only amounts to 31 cm. or about one English foot. This subject is further considered in Book III. Part I. Sect. iii.

The water of the ocean is distinguished from ordinary terrestrial waters by a higher specific gravity, and the presence of so large a proportion of saline ingredients as to impart a strongly salt taste. The average density of sea-water is about 1·026, but it varies slightly in different parts even of the same ocean. According to the observations of J. Y. Buchanan during the *Challenger* expedition, some of the heaviest sea-water occurs in the pathway of the trade-winds of the North Atlantic, where evaporation must be comparatively rapid, a density of 1·02781 being registered. Where, however, large rivers enter the sea, or where there is much melting ice, the density diminishes; Buchanan found among the broken ice of the Antarctic Ocean that it had sunk to 1·02418.[3] A

[1] H. Bruns, 'Die Figur der Erde,' Berlin, 1878; R. S. Woodward, *Bull. U. S. G. S.* No. 48, p. 85 (1888).

[2] Börsch-Kühnen, 'Vergleichung der Mittelwasser der Ostsee und Nordsee, des Atlantischen Ozeanes, und des Mittelmeeres,' Berlin, 1891; Czuber, "Geometrische Nivellement," *Technische Blätter*, xxiii. Hefte 2 und 3.

[3] Buchanan, *Proc. Roy. Soc.* (1876), xxiv.

series of soundings taken during the *Vega* expedition in the Kara Sea (lat. 76° 18′, long. 95° 30′ E.) gave a progressive increase of salinity from 1·1 at the surface to 3·4 at 30 fathoms, the surface being freshened by the water poured into the sea by the Siberian rivers.[1]

The greater density of sea-water depends, of course, upon the salts which it contains in solution. At an early period in the earth's history, the water now forming the ocean, together with the rivers, lakes, and snowfields of the land, existed as vapour, in which were mingled many other gases and vapours, the whole forming a vast atmosphere surrounding the still intensely hot globe. Under the enormous pressure of the primeval atmosphere, the first condensed water might have had a temperature little below the critical one.[2] In condensing, it would carry down with it many substances in solution. The salts now present in sea-water are to be regarded as partially derived from the primeval constitution of the sea, and thus we may infer that the sea has always been more or less saline. Professor Joly estimates the probable original proportion of chlorides in the primeval ocean to have been about 10·7 per cent of the present amount, the remaining large percentage having been since supplied to the sea by rivers carrying salts in solution from the land.[3]

But it is manifest that, whatever may have been the original composition of the oceans, they have for a vast section of geological time been constantly receiving mineral matter in solution from the land. Every spring, brook, and river removes various salts from the rocks over which it moves, and these substances, thus dissolved, eventually find their way into the sea. Consequently sea-water ought to contain more or less traceable proportions of every substance which the terrestrial waters can remove from the land—in short, of probably every element present in the outer shell of the globe, for there seems to be no constituent of the earth which may not, under certain circumstances, be held in solution in water. Moreover, unless there be some counteracting process to remove these mineral ingredients, the ocean-water ought to be growing, insensibly perhaps, salter, for the supply of saline matter from the land is incessant. It has been ascertained indeed, with some approach to certainty, that the salinity of the Baltic and Mediterranean is gradually increasing.[4]

[1] O. Pettersson, 'Vega-Expeditionens Vetenskapliga Iakttagelser,' ii., Stockholm, 1883. The specific gravity of the waters of the sea has been carefully investigated by Dr. Buchan, *Trans. Roy. Soc. Edin.* 1896. A summary of his work will be found in *Nature*, liv. (1896), p. 235.

[2] See a paper by Professor J. Joly, "An Estimate of the Geological Age of the Earth," *Sci. Trans. Roy. Dublin Soc.* ser. 2, vii. (1899), pp. 23-65. In this paper an account is given of the probable stages in the condensation and composition of the ocean. See also *Q. J. G. S.* xxxvi. (1880), pp. 112, 117; Rev. O. Fisher, 'Physics of the Earth's Crust,' 2nd edit. p. 148.

[3] Sterry Hunt supposed that the saline waters of North America derive their mineral ingredients from the sediments and precipitates of the sea in which the Palæozoic rocks were deposited. 'Geological and Chemical Essays,' p. 104. There is evidence among the geological formations that large quantities of lime, silica, chlorides, and sulphates have in the course of time been removed from the sea.

[4] Paul, in Watt's 'Dictionary of Chemistry,' v. p. 1020. For a detailed study of the

The average proportion of saline constituents in the water of the great oceans far from land is about three and a half parts in every hundred of water.[1] But in enclosed seas, receiving much fresh water, it is greatly reduced, while in those where evaporation predominates it is correspondingly augmented. Thus the Baltic water contains from one-seventh to nearly a half of the ordinary proportion in ocean water, while the Mediterranean contains sometimes one-sixth more than that proportion. Forchhammer detected the presence of the following twenty-seven elements in sea-water: oxygen, hydrogen, chlorine, bromine, iodine, fluorine, sulphur, phosphorus, nitrogen, carbon, silicon, boron, silver, copper, lead, zinc, cobalt, nickel, iron, manganese, aluminium, magnesium, calcium, strontium, barium, sodium, and potassium.[2] To these may be added arsenic, lithium, caesium, rubidium, gold,[3] and probably most if not all of the other elements, though in proportions too minute for detection. The chief constituents have been determined by Dittmar to be present in the proportions shown in the first column of the subjoined tables. Assuming them to occur in the combinations shown in the second column, they are present in the average ratios therein stated.[4] The third column shows the proportions of the different chemical elements in the composition of the waters of the ocean as a whole:—[5]

Eastern Mediterranean, see the Reports of a Commission, *Denksch. Akad. Wiss.*, Vienna, 1892 *et seq.*

[1] Dittmar's elaborate researches on the samples of ocean water collected by the *Challenger* Expedition show that the lowest percentage of salts obtained was 3·301, from the southern part of the Indian Ocean, south of lat. 66°, while the highest was 3·737, from the middle of the North Atlantic, at about lat. 23°. Some valuable results from observations on the waters of the North Atlantic are given by H. Tornoe and L. Schmelck in the *Report of the Norwegian North-Atlantic Expedition*, 1876-78. The average proportion of salts was found to be from 3·47 to 3·51 per cent, the mean quantities of each constituent as estimated being as follow: $CaCO_3$, 0·002; $CaSO_4$, 0·1395; $MgSO_4$, 0·2071; $MgCl_2$, 0·3561; KCl, 0·747; $NaHCO_3$, 0·0166; NaCl, 2·682.

[2] Forchhammer, *Phil. Trans.* clv. p. 295. According to Thorpe and Morton (*Chem. Soc. Journ.* xxiv. p. 507), the water of the Irish Sea contains in summer rather more salts than in winter. In 1000 grammes of the summer water of the Irish Sea they found 0·04754 grammes of carbonate of lime, 0·00503 of ferrous carbonate and traces of silicic acid. For exhaustive chemical investigations regarding the chemistry of ocean water consult Dittmar in vol. i. "Physics and Chemistry," *Report of Voyage of the Challenger*, 1884; also the "Chemistry" part of the *Report of the Norwegian North-Atlantic Expedition*, 1876-78.

[3] Prof. Liversidge has estimated, as the result of numerous analyses, that the sea-water off the coast of New South Wales contains from about 0·5 to 1 grain of gold per ton, or in round numbers 130 to 260 tons of gold per cubic mile, and he points out that at this proportion there may be more than 75,000,000,000 tons of gold in the waters of the whole oceans of the globe. *Proc. Roy. Soc. N. S. Wales*, 2nd Oct. 1895. Professor W. Ramsay remarks also that "sea-water sometimes contains a grain of gold per ton, that is, one part in 15,180,000," *Nature*, lxv. (1901), p. 164.

[4] Dittmar, *op. cit.* p. 203 *et seq.* For further reference to the chemistry of sea-water, especially in connection with the action of marine organisms, see Book III. Part II.

[5] Mr. F. W. Clarke, *Bull. U. S. G. S.* No. 78 (1891), p. 35. He remarks that in this allocation of the several proportions of the elements, dissolved gases need not be taken into account, and that the other elements not here named are present in such minute quantities that no one of them can reach 0·001 of 1 per cent.

| I | | II | | III | |
|---|---|---|---|---|---|
| Chlorine | 55·292 | Chloride of sodium | 77·758 | Oxygen | 85·79 |
| Bromine | 0·188 | Chloride of magnesium | 10·878 | Hydrogen | 10·67 |
| Sulphuric acid, $SO_3$ | 6·410 | Sulphate of magnesia | 4·737 | Chlorine | 2·67 |
| Carbonic acid, $CO_2$ | 0·152 | Sulphate of lime | 3·600 | Sodium | 1·14 |
| Lime, CaO | 1·676 | Sulphate of potash | 2·465 | Magnesium | 0·14 |
| Magnesia, MgO | 6·209 | Bromide of magnesium | 0·217 | Calcium | 0·05 |
| Potash, KO | 1·332 | Carbonate of lime | 0·345 | Potassium | 0·04 |
| Soda, $Na_2O$ | 41·234 | | | Sulphur | 0·09 |
| Subtract Basic Oxygen equivalent to the Halogens | 12·493 | | | Bromine | 0·008 |
| | | | | Carbon | 0·002 |
| Total Salts | 100·000 | Total Salts | 100·000 | | 100·000 |

Sea-water is appreciably alkaline, its alkalinity being due to the presence of carbonates, of which carbonate of lime is one.[1] In addition to its salts it always contains dissolved atmospheric gases. From the researches conducted during the voyage of the *Bonité* in the Atlantic and Indian Oceans, it was estimated that the gases in 100 volumes of sea-water ranged from 1·85 to 3·04, or from two to three per cent. From observations made during the *Porcupine* cruise of 1868, it was ascertained that the proportion of oxygen was greatest in the surface water, and least in the bottom water. The dissolved oxygen and nitrogen are doubtless absorbed from the atmosphere, the proportion so absorbed being mainly regulated by temperature. According to Dittmar's determinations, a litre of sea-water at 0° C. will take up 15·60 cubic centimetres of nitrogen and 8·18 of oxygen, while at 30° C. the proportions sink respectively to 8·36 and 4·17. He regarded the carbonic acid as occurring chiefly as carbonates, its presence in the free state being exceptional. During the voyage of the *Challenger*, Buchanan ascertained that the proportion of carbonic acid is always nearly the same for similar temperatures, the amount in the Atlantic surface water, between 20° and 25° C., being 0·0466 gramme per litre, and in the surface Pacific water 0·0268; and that sea-water contains sometimes at least thirty times as much carbonic acid as an equal bulk of fresh water would do.[2] A supposed greater proportion of carbonic acid in the deeper and colder waters of the ocean has been suggested as the main cause of the disappearance of the larger and more delicate calcareous pelagic organisms from abysmal deposits, these forms being more readily attacked and carried away in solution; but according to Dittmar, even alkaline sea-water, if given sufficient time, will take up carbonate of lime

[1] Dittmar, *op. cit.* p. 206.

[2] *Proc. Roy. Soc.* xxiv. According to Mr. Tornöe (*Norwegian North-Atlantic Expedition*, 1876-78, "Chemistry") most of the carbonic acid of sea-water is in combination with soda as bicarbonate of soda. See his memoir for an estimate of the proportion of air in sea-water; also J. Y. Buchanan, *Nature*, xxv. p. 386. Dittmar, *op. cit.* p. 209. The student will find a detailed discussion of "The Carbon-dioxide of the Ocean and its relations to the Carbon-dioxide of the Atmosphere," in a paper by Mr. Cyrus F. Tolman, jun., *Journ. Geol.* vii. (1899), pp. 585-618.

in addition to what it already contains.[1] Another of the constituents of sea-water is diffused organic matter, derived from the bodies of dead plants and animals, and no doubt of great importance as furnishing food for the lower grades of animal life.[2] It has been ascertained that in the Black Sea there is a remarkable development of sulphuretted hydrogen, which gradually increases with the depth until in the bottom waters, 1200 fathoms from the surface, the proportion rises to 655 cubic centimetres in 100 litres. This gas appears to be liberated by the action of certain microbes upon organic matter, and even upon the sulphates and sulphides present in solution in the water.[3]

In working up the results of the *Challenger* expedition, the late Professor Tait had occasion to make some experiments which proved that sea-water is sensibly compressible by its own weight, the compressibility increasing by about one ton per square inch for every mile of descent below the surface. At the bottom of the abysses, at a depth of six miles, this pressure must amount to 1000 atmospheres. The result of this compression is to make the surface-level of the general mass of the oceans some 116 feet lower than it would be if the water were perfectly incompressible. If the water ceased to be compressible, the effect would be to submerge 2,000,000 square miles of land, about 4 per cent of the whole.[4]

## II.—*The Solid Globe or Lithosphere.*

Within the atmospheric and oceanic envelopes lies the inner solid globe. The only portion of it which, rising above the sea, is visible to us, and forms what we term Land, occupies rather more than one-fourth of the total superficies of the globe, or about 55,000,000 square miles.

§ 1. **The Outer Surface.**—The land is placed chiefly in the northern hemisphere and is disposed in large masses, or continents, which taper southwards to about half the distance between the equator and the south pole. No adequate cause has yet been assigned for the present distribution of the land. It can be shown, however, that portions of the continents are of extreme geological antiquity. There is reason to believe, indeed, that the present terrestrial areas have on the whole been land, or have, at least, never been submerged beneath deep water, from the time of the earliest stratified formations; and that, on the other hand, the ocean-basins have probably always been vast areas of depression. This subject will be discussed in subsequent pages.

In the New World, the continental trend is approximately north and south; in the Old World, it ranges east and west along its northern

[1] *Op. cit.* p. 222.

[2] Different estimates have been made of the proportion of organic matter. According to the researches of L. Schmelck (*Norwegian North-Atlantic Expedition*, 1876-78, part ix. p. 4), the proportion of 0·0025 gramme in 100 c.c. of water.

[3] N. Androussow, "La Mer Noire," *Guide des Excursions VII^me Congr. Géol. Internat.* No. xxix (1897), p. 6.

[4] *Challenger Report*, "Physics and Chemistry," ii. part i. p. 76.

extent, and sends two long tongues southward, one of which forms the continent of Africa, the other the vast chain of islands which terminates in Tasmania. A remarkable line of partition, which has already been alluded to, divides the continental masses into northern and southern regions. This line of severance is complete between Europe and Africa, and between Asia and Australasia, though between North and South America a narrow strip of land connects the two continents.

The general features of continental structure, and especially the intimate relation that may be traced between the general trend of the land areas and the direction of the mountain-chains, are best displayed in the New World, where both North and South America may be studied as typical embodiments of these leading characteristics. It is there seen how the land reaches its highest elevation along the margin that faces the larger ocean, while minor and less connected ranges of hills rise upon the opposite border. We observe also that the dominant trend of the continental mass reaches its culminating line along the great backbone of mountains that stretches almost continuously from Cape Horn into the Arctic Ocean, from which line of upheaved ground broad plateaux and lower plains descend towards the Atlantic.

While any good map of the globe enables us to see at a glance the relative positions and areas of the continents and oceans, most maps fail to furnish any data by which the general height or volume of a continent may be estimated. As a rule, the mountain-chains are exaggerated in breadth, and incorrectly indicated, while no attempt is made to distinguish between high plateaux and low plains. In North America, for example, a continuous shaded ridge is placed down the axis of the continent, and marked "Rocky Mountains," while the vast level or gently rolling prairies are left with no mark to distinguish them from the maritime plains of the eastern and southern states. In reality there is no such one continuous mountain-chain. The so-called "Rocky Mountains" consist of many independent and sometimes widely separated ridges, having a general meridional trend, and rising above a vast plateau, which is itself 4000 or 5000 feet in elevation. It is not these intermittent ridges which really form the great mass of the land in that region, but the widely extended lofty plateau, or rather succession of plateaux, which supports them. In Europe, also, the Alps form but a subordinate part of the total bulk of the land. If their materials could be spread out over the continent, it has been calculated that they would not increase its height more than about twenty-one feet.

Attempts have been made to calculate the probable average height which would be attained if the various inequalities of the land could be levelled down. Humboldt estimated the mean height of Europe to be about 671, of Asia 1132, of North America 748, and of South America 1151 feet.[1] Herschel supposed the mean height of Africa to be 1800 feet.[2] These figures, though based on the best data available at the time, were much under the truth. In particular, the average height assigned to North America was evidently far less than it should

[1] 'Asie Centrale,' tome i. p. 168. [2] 'Physical Geography,' p. 119.

be; for the great plains west of the Mississippi valley reach an altitude of about 5000 feet, and serve as the platform from which the mountain ranges rise. The height of Asia also is obviously much greater than this old estimate. G. Leipoldt subsequently computed the mean height of Europe to be 296·838 metres (973·628 feet).[1] Professor A. De Lapparent made the mean height of the land of the globe 2120 feet, and estimated the mean height of Europe to be 958 feet, Asia 2884, Africa 1975, North America 1952, and South America 1762.[2] Sir John Murray computed these heights as follows: Europe 939, Asia 3189, Africa 2021, North America 1888, South America 2078, Australia 805 feet; general mean height of land, 2252 feet.[3] Subsequently the subject has been reinvestigated by the late General De Tillo,[4] Dr. Hugh R. Mill,[5] Dr. Supan,[6] and Professor Penck.[7] It is of some consequence to obtain as near an approximation to the truth in this matter as may be possible, in order to furnish a means of comparison between the relative bulk of different continents, and the amount of material on which geological changes can be effected. The latest general results of the various estimates as to the area and height of the continents are embodied in the subjoined table:—

| Continent. | Area in Sq. Miles. | Mean Height. | Greatest Elevation in Feet. |
|---|---|---|---|
| Europe . . . | 3,700,000 | 330 metres (1032 feet) | 18,500 |
| Asia . . . | 16,400,000 | 1010 ,, (3313 ,, ) | 29,000 |
| Africa . . . | 11,100,000 | 660 ,, (2165 ,, ) | 18,800 |
| Australia . . | 3,000,000 | 310 ,, (1017 ,, ) | 7,200 |
| North America . | 7,600,000 | 650 ,, (2132 ,, ) | 18,200 |
| South America . | 6,800,000 | 650 ,, (2132 ,, ) | 22,400 |
| All Countries . . | 55,000,000 | 735 ,, (2411 ,, ) | 29,000 |

The highest elevation of the surface of the land is the summit of Mount Everest, in the Himalaya range (29,000 feet); the deepest depression not covered by water is that of the shores of the Dead Sea (1300 feet below sea-level). There are, however, many subaqueous portions of the land which sink to greater depths. The bottom of the Caspian Sea, for instance, lies about 3000 feet below the general sea-

[1] 'Die Mittlere Hohe Europas,' Leipzig, 1874. In this work the mean height of Switzerland is put down as 1299·91 metres; Spanish peninsula, 700·60; Austria, 517·87; Italy, 517·17; Scandinavia, 428·10; France, 393·84; Great Britain, 217·70; German Empire, 213·66; Russia, 167·09; Belgium, 163·36; Denmark (exclusive of Iceland), 35·20; the Netherlands (exclusive of Luxembourg and the tracts below sea-level), 9·61.

[2] 'Traité de Géologie,' p. 56. [3] *Scottish Geog. Mag.* iv. (1888), p. 23.

[4] "Die Mittlere Höhe der Kontinente und die Mittlere Tiefe der Ozeane," etc., *Iswestija. Russ. Geograph. Ges.* xxv. (1889), p. 113; *Petermann's Mitth.* (1889), p. 48.

[5] "The Vertical Relief of the Globe," *Scottish Geog. Mag.* vi. (1900), p. 182.

[6] *Petermann's Mitth.* 1889, p. 17. See also the summary of the subject in his 'Grundzüge der Physischen Erdkunde,' 1896, p. 36.

[7] See his 'Morphologie der Erdöberfläche,' i. pp. 146-152, and authorities there cited.

level. The vertical difference between the highest point of the land and the maximum known depth of the sea is 59,930 feet or more than 11 miles.

There are two conspicuous junction-lines of the land with its overlying and surrounding envelopes. First, with the Air, expressed by the contours or relief of the land. Second, with the Sea, expressed by coast-line.

(1) Contours or Relief of the Land.—While the surface of the land presents endless diversities of detail, its leading features may be generalised as mountains, table-lands, and plains.

*Mountains.*—The word "mountain" is, properly speaking, not a scientific term.[1] It includes many forms of ground utterly different from each other in size, shape, structure, and origin. It is popularly applied to any considerable eminence or range of heights, but the height and size of the elevated ground so designated vary indefinitely. In a really mountainous country the word would be restricted to the loftier masses of ground, while such a word as hill would be given to the lesser heights. But in a region of low or gently undulating land, where any conspicuous eminence becomes important, the term mountain is lavishly used. In Eastern America this habit has been indulged in to such an extent, that what are, so to speak, mere hummocks in the general landscape, are dignified by the name of mountains.

It is hardly possible to give a precise scientific definition to a term so vaguely employed in ordinary language. When a geologist uses the word, he must either be content to take it in its familiar vague sense, or must add some phrase defining the meaning which he attaches to it. He finds that there are four leading and distinct types of elevation which are all popularly termed mountains, and each of which is susceptible of subdivision into further groups.

(*a*) Volcanic mountains, formed by the accumulation of materials ejected from the earth's interior and piled up into a conical mass round the vent from which they proceed. Such eminences may be of any size, from mere hillocks, like some of the Puys of Central France, up to the most gigantic masses, such as Etna, Teneriffe, and Cotopaxi.

(*b*) Outlier mountains, produced by the isolation of large, more or less conical or flat-topped masses during the course of prolonged denudation. Such detached outliers are more especially frequent fronting the escarpments of thick groups of sedimentary formations. Where they consist of flat or slightly inclined strata they generally display parallel lines along their sides, caused by the influence of the harder and softer layers in the stratification. Conspicuous examples of this type of mountain-form are presented by the Torridon Sandstone of the north-west of Scotland, where some of the isolated masses range from 3000 to 4000 feet in height. The remarkable Buttes of Western America are well-known instances of a similar structure and scenery (Book VII.).

(*c*) Closely connected with the last-named type is that of denudation ridges. These consist of eminences, often hundreds or thousands of feet in height, connected at the sides or base, and forming long lines of winding ridges or chains of uplands. They are marked by the distinctive feature that their forms are not directly due to any internal

[1] A useful compendium of information regarding the mountain chains of the globe will be found in R. von Lendenfeld's 'Die Hochgebirge der Erde,' pp. xiv, 232, Freiburg im Breisgau, 1899.

structure of their component rocks, but have resulted from the unequal effects of denudation. They are masses of ground left after the erosion of the system of valleys by which they are traversed. Many of the more ancient table-lands both in the Old World and the New furnish examples of this type, such as the highlands of Scotland, the hills of Cumberland and Wales, the chain of fjelds in Scandinavia, the uplands between Bohemia and Bavaria, the Laurentide Mountains of Canada, and the Green and White Mountains of New England. Every stage in the evolution of this kind of topography may be exemplified, the earliest being furnished by the more recent formations such as the Tertiary basalts of Iceland, the Faroe Isles, and the west of Scotland, and the clays, sandstones, and limestones of the Central and Western States of America.

(*d*) Tectonic mountains, consisting of chains of ridges that rise into a succession of more or less distinct summits, and are separated by lines of valleys. The broad distinction of this type is that it has been produced by the plication and elevation of the earth's crust. In some cases, like the Jura, the crust has been thrown into long folds, without serious rupture ; but in the more important examples, like the Alps, the crust has not only been plicated but dislocated, and large portions of it have been overturned and thrust over each other. In the course of ages of denudation the original topography due immediately to underground disturbance has been profoundly modified, but the great mountain masses remain as memorials of the gigantic upheavals that gave them birth. It is these heights that in a geological sense are the only true mountain-ranges. They may be looked upon as the crests of the great waves into which the crust of the earth has been thrown. All the great mountain-lines of the world belong to this type.

Leaving further details of mountain-topography to be given in Book VII., we may confine our attention here to a few of the more important general features. In elevations of the fourth or true mountain type, there may be either one line or range of heights, or a series of parallel and often coalescent ranges. In the Western Territories of the United States, the vast plateau has been, as it were, wrinkled by the uprise of long intermittent ridges, with broad plains and basins between them. Each of these forms an independent mountain-range. In the heart of Europe, the Bernese Oberland, the Pennine, Lepontine, Rhaetic, and other ranges form one great Alpine chain or system.

In a great mountain-chain, such as the Alps, Himalayas, or Andes, there is one general persistent trend for the successive ridges. Here and there, lateral offshoots may diverge, but the dominant direction of the axis of the main chain is generally observed by its component ridges until they disappear. Yet while the general parallelism is preserved, no single range may be traceable for more than a comparatively short distance ; it may be found to pass insensibly into another, while a third may be seen to begin on a slightly different line, and to continue with the same dominant trend until it in turn becomes confluent. The various ranges are thus apt to assume an arrangement *en échelon.*

The ranges are separated by *longitudinal* valleys, that is, depressions coincident with the general direction of the chain. These, though sometimes of great length, are relatively of narrow width. The valley of the Rhône, from the source of the river down to Martigny, offers an excellent example. By a second series of valleys the ranges are trenched, often to a great depth, and in a direction transverse to the general trend. The Rhône furnishes also an example of one of these *transverse* valleys, in its course from Martigny to the Lake of Geneva. In most mountain

regions, the heads of two adjacent transverse valleys are often connect by a depression or *pass* (*col, joch*).


Fig. 2.—Section from the Jura to Mont Blanc, on the same scale for length and height. J, Jura; s, Lake of Geneva; v, Voirons; m, Mole; a, Aiguille de Varens; b, Brevent; MB, Mont Blanc.

A large block of mountain ground, rising into one more dominant summits, and more or less distinctly defin by longitudinal and transverse valleys, is termed in Fren a *massif*—a word for which there is no good English eq valent. Thus in the Swiss Alps we have the massifs of t Glärnisch, the Tödi, the Matterhorn, the Jungfrau, etc.

Very exaggerated notions are common regarding t angle of declivity in mountains. Sections drawn across a mountain or mountain-chain on a true scale, that is, wi the length and height on the same scale, bring out t fact that, even in the loftiest mountains, the breadth base is always very much greater than the height. Actu

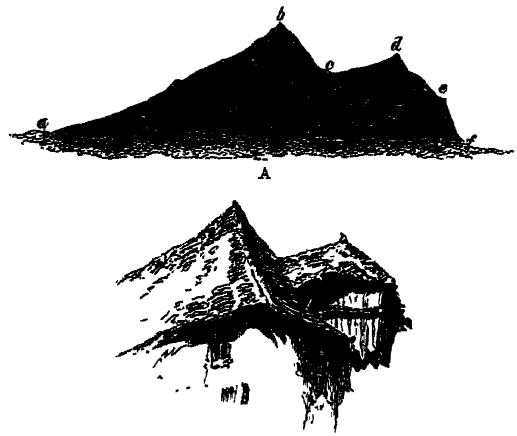


Fig. 1.—Angles of Slope where the eye may be deceived by perspective. (After Ruskin.) A, Mountain outline; B, The same outline as shown by cottage roof.

vertical precipices are less frequent than is usually supposed, and even when they do occur, generally form minor incidents in the declivities of mountains. Slopes of more than 30° in angle are likewise far less abundant than casual tourists believe. Even such steep declivities as those of 38° or 40° are most frequently found as *talus*-slopes at the foot of crumbling cliffs, and represent the angle of repose of the disintegrated débris. Here and there, where the blocks loosened by weathering are of large size, they may accumulate upon each other in such a manner that for short distances the average angle of declivity may mount as high as 65°. But such steep slopes are of limited extent. Declivities exceeding 40°, and bearing a large proportion to the total dimensions of hill or mountain, are always found to consist of naked solid rock.

In estimating angles of inclination from a distance, the student will learn by practice how apt is the eye to be deceived by perspective and to exaggerate the true declivity, sometimes to mistake a horizontal for a highly inclined or vertical line. The mountain outline shown in Fig. 1 presents a slope of 25° between *a* and *b*, of 45° between *b* and *c*, of 17° between *c* and *d*, of 40° between *d* and *e*, and of 70° between *e* and *f*. At a great distance, or with bad conditions of atmosphere, these might be believed to be the real declivites. Yet if the same angles be observed in another way (as on a cottage roof at B), we may learn that an apparently inclined surface may really be horizontal (as from *a* to *b* and from *c* to *d*), and that by the effect of perspective, slopes may be made to appear much steeper than they really are.[1]

Much evil has resulted in geological research from the use of exaggerated angles of slope in sections and diagrams. It is therefore desirable that the student should, from the beginning, accustom himself to the drawing of outlines as nearly as possible on a true scale. The accompanying section of the Alps by De la Beche (Fig. 2) is of interest in this respect, as one of the earliest illustrations of the advantage of constructing geological sections on a true scale as to the relative proportions of height and length.[2]

*Table-lands* or *Plateaux* are elevated regions of flat or undulating country, rising to heights of 1000 feet and upwards above the level of the sea. They are sometimes bordered with steep slopes, which descend from their edges, as the table-land of the Spanish peninsula does into the sea. In other cases, they gradually sink into the plains and have no definite boundaries; thus the prairie-land west of the Missouri slowly and imperceptibly ascends until it becomes a vast plateau from 4000 to 5000 feet above the sea. Occasionally a high table-land is encircled with lofty mountains, as in those of Quito and Titicaca among the Andes, and that of the heart of Asia; or it forms in itself the platform on which lines of mountains stand, as in North America, where the ranges included within the Rocky Mountains reach elevations of from 10,000 to 14,000 feet above the sea, but no more than from 5000 to 10,000 feet above the table-land.

Two types of table-land structure may be observed. 1. Table-lands consisting of level or gently undulated sheets of rock, the general surface of the country corresponding with that of the stratification. The Rocky Mountain plateau is an example of this type, which may be called that of Deposit, for the flat strata have been equably upraised nearly in the position in which they were deposited. 2. Table-lands formed out of contorted, crystalline, or other rocks, which have been planed down by superficial agents. This type, where the external form is independent of

[1] Mr. Ruskin has well illustrated this point. See 'Modern Painters,' vol. iv. p. 183, whence the illustrations in Fig. 1 are taken.

[2] 'Sections and Views, illustrative of Geological Phenomena,' 1830. 'Geol. Observer,' p. 646. Excellent models for the graphic and at the same time artistic rendering of geological sketches and sections may be found in the admirable illustrations drawn by Professor Heim of Zurich in his work on the 'Mechanismus der Gebirgsbildung,' and in his contributions to the *Beiträge zur Geologischen Karte der Schweiz.*

geological structure, may be termed that of Erosion. The *fjelds* of Norway are portions of such a table-land. In proportion to its antiquity, a plateau is trenched by running water into systems of valleys, until in the end it may lose its plateau character and pass into the second type of mountain-ground above described. This change has largely altered the ancient table-lands of the Scottish Highlands and of Scandinavia.

*Plains* are tracts of lowland (under 1000 feet in height) which skirt the sea-board of the continents and stretch inland up the river-valleys. The largest plain in the world is that which, beginning in the centre of the British Islands, stretches across Europe and Asia. On the west, it is bounded by the ancient table-lands of Scandinavia, Scotland, and Wales on the one hand, and those of Spain, France, and Germany on the other. Most of its southern boundary is formed by the vast belt of high ground which spreads from Asia Minor to the east of Siberia. Its northern margin sinks beneath the waters of the Arctic Ocean. This vast region is divided into an eastern and western tract by the low chain of the Ural Mountains, south of which its general level sinks, until underneath the Caspian Sea it reaches a depression of about 3000 feet below sea-level. Along the eastern sea-board of America lies a broad belt of low plains, which attain their greatest dimensions in the regions watered by the larger rivers. Thus they cover thousands of square miles on the north side of the Gulf of Mexico, and extend for hundreds of miles up the valley of the Mississippi. Almost the whole of the valleys of the Orinoco, Amazon, and La Plata is occupied with vast plains.

From the evidence of upraised marine shells, it is certain that large portions of the great plain of the Old World comparatively recently formed part of the sea-floor. On the other hand, the beds of some enclosed sea-basins, such as that of the North Sea, have at no very remote date been plains of the dry land.

It is obvious, from their distribution along river-valleys, and on the areas between the base of high grounds and the sea, that plains are essentially areas of deposit. They are the tracts that have received the detritus washed down from the slopes above them, whether that detritus has originally accumulated on the land or below the sea. Their surface presents everywhere loose sandy, gravelly, or clayey formations, indicative of its comparatively recent subjection to the operation of running water.

(2) Coast-lines.—A mere inspection of a map of the globe brings before the mind the striking differences which the masses of land present in their line of junction with the sea. As a rule, the southern continents possess a more uniform unindented coast-line than the northern. It has been estimated that the ratios between area and coast-line among the different continents stand approximately as in the following table from E. Reclus :—

| | | | | | |
|---|---|---|---|---|---|
| Northern | Europe | has 1 kilometre of coast-line | to | 289 | square kilometres of surface. |
| | North America | ,, | ,, | 407 | ,, |
| | Asia | ,, | ,, | 763 | ,, |
| Southern | Africa | ,, | ,, | 1420 | ,, |
| | South America | ,, | ,, | 689 | ,, |
| | Australia | ,, | ,, | 534 | ,, |

It will be seen that Europe is the continent most abundantly penetrated by indentations of the sea. Some portions of it are specially remarkable in this respect, particularly Scandinavia in the north and Greece and Turkey in the south. Reference to the map will show also that in the American continent a remarkable increase in the proportion of coast-line to area is traceable both towards the extreme north and extreme south. This increase is particularly marked south of lat. 40° S.

In estimating the relative potency of the sea and of the atmospheric agents of disintegration, in the task of wearing down the land, it is evidently of great importance to take into account the amount of surface respectively exposed to their operations. Other things being equal, there is relatively more marine erosion in Europe than in North America. But we require also to consider the nature of the coast-line, whether flat and alluvial, or steep and rocky, or with some intermediate blending of these two characters. By attending to this point, we are soon led to observe such great differences in the character of coast-lines, and such an obvious relation to differences of geological structure, on the one hand, and to diversities in the removal or deposit of material, on the other, as to suggest that the present coast-lines of the globe cannot be aboriginal, but must be referred to the operation of geological agents still at work. This inference is amply sustained by more detailed investigation. While the general distribution of land and water and the main trend of the lines of junction between them must undoubtedly be assigned to terrestrial movements affecting the solid globe, the details of the present actual coasts of the land have evidently been chiefly produced by local and especially superficial causes. The most effective of these causes has been the influence of the various agents of denudation. In general it may be said that headlands project from the land because they consist of rock which has been better able to withstand the shock of the breakers, and that, on the other hand, bays and creeks have been cut out of less durable material, which offered a feebler resistance to the inroads of the sea. A highly important influence on the form of the coast has been exerted by movements of elevation and depression. By the sinking of land, ranges of hills have become capes and headlands, while the valleys have passed into the condition of bays, inlets, or fjords. By the uprise of the sea-bottom, tracts of low alluvial ground have been added to the land. Again, for many hundreds of miles both in the old and new worlds the coast-line has been altered by the deposition of long bars of sediment. These bars, so conspicuous, for example, in Europe from Antwerp to the Scager Rack, all along the south coast of Iceland, and in the United States from the Florida Channel to New Jersey, keep back the sea from encroaching on the land, so that where the supply of sediment compensates for what is swept away by the waves and currents from the bars, the coast inside may remain for a long period with hardly any change, or may even grow out into the protected water of the lagoons. It is thus evident that speculations as to the history of the elevation of the land, based merely upon inferences from the form of coast-lines as expressed upon ordinary maps, can hardly be of much real service. To make them

worthy of consideration demands a careful scrutiny of the actual coast-lines, and an amount of geological investigation which would require long and patient toil for its accomplishment.

Passing from the mere external form of the land to the composition and structure of its materials, we may begin by considering the general density of the entire globe, computed from observations and compared with that of the outer and accessible portion of the planet. Reference has already been made to the comparative density of the earth among the other members of the solar system. In inquiries regarding the history of our globe, the density of the whole mass of the planet, as compared with water—the standard to which the specific gravities of terrestrial bodies are referred—is a question of prime importance. Various methods have been employed for determining the earth's density. The deflection of the plumb-line on either side of a mountain of known structure and density, the time of oscillation of the pendulum at great heights, at the sea-level, and in deep mines, and the comparative force of gravitation as measured by the torsion balance, have each been tried with the following various results:—

| | | | |
|---|---|---|---|
| Plumb-line experiments on Schichallien (Maskelyne and Playfair) gave as the mean density of the earth | | | 4·713 |
| Do. on Arthur's Seat, Edinburgh (James) | | | 5·316 |
| Pendulum experiments on Mont Cenis (Carlini and Giulio) | | | 4·950 |
| Do. in Harton coal-pit, Newcastle (Airy) | | | 6·565 |
| Torsion balance experiments | | (Cavendish, 1798) | 5·480 |
| Do. | do. | (Reich, 1838) | 5·49–5·58 |
| Do. | do. | (Baily, 1843) | 5·660 |
| Do. | do. | (Cornu and Baille, 1870) | 5·56–5·50 |
| Common balance (von Jolly, 1879-80) | | | 5·692 |
| Do. | do. | (J. H. Poynting, 1878-90) | 5·493 |
| Pendulum balance (Uilsing, 1886-88) | | | 5·594 5·577 |
| Improved torsion balance (C. V. Boys) | | | 5·5270 |
| Double balance (Richard and Krigar-Menzel, 1884-93) | | | 5·505 |
| Torsion (Braun, 1892-94) | | | 5·520–5·531 |
| Pendulum (G. R. Putnam, 1895) | | | 5·63 |

Though these observations are somewhat discrepant, we may feel satisfied that the globe has a mean density neither much more nor much less than 5·5; that is to say, it is five and a half times heavier than one of the same dimensions formed of pure water. Now the average density of the materials which compose the accessible portions of the earth is between 2·5 and 3; so that the mean density of the whole globe is about twice as much as that of its outer part. We may, therefore, infer that the inside consists of heavier materials than the outside, and consequently that the mass of the planet must contain at least two dissimilar portions—an exterior lighter crust or rind, and an interior heavier nucleus.[1]

[1] The importance of obtaining numerous pendulum observations for geological as well as geodetical purposes is now being realised. See Mr. Putnam's paper, "Results of a Trans-continental Series of Gravity Measurements," with notes by Mr. G. K. Gilbert, *Bull. Phil.*

§ 2. **The Crust.**—It was formerly the prevalent belief that the exterior and interior of the globe differ from each other to such an extent that, while the outer parts are cool and solid, the vastly more enormous inner intensely hot part is more or less completely liquid. Hence the term "crust" was applied to the external rind in the usual sense of that word. This crust was variously computed to be ten, fifteen, twenty, or more miles in thickness. In the accompanying diagram (Fig. 3), for example, the thick line forming the circle represents a relative thickness of 100 miles. There are so many proofs of enormous and widespread corrugation of the materials of the earth's outer layers, and such abundant traces of former volcanic action, that geologists have naturally regarded the doctrine of a thin crust over a liquid interior as necessary for the explanation of a large class of terrestrial phenomena. This doctrine, as will be afterwards more fully explained, has been opposed by eminent physicists, and was reluctantly abandoned by most geologists. Nevertheless, the term "crust" has continued to be used, apart from all theory regarding the nucleus, as a convenient word to denote those cool, solid upper or outer layers of the earth's mass in the structure and history of which, as the only portions of the planet accessible to human observation, lie the chief materials of geological investigation. The tendency of the most recent reconsideration of the question from the physical side is rather to sustain the idea that the "crust" really does represent an external solid shell enclosing a partly liquid, partly gaseous interior. This subject is discussed at p. 65, while the chemical and mineral constitution of the crust is fully treated in Part II. of this Book.

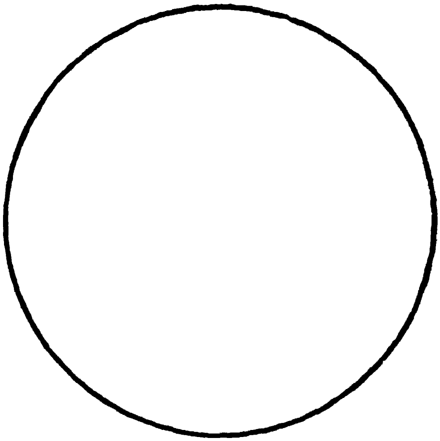

Fig. 3.—Supposed Crust of the Earth, 100 Miles thick.

§ 3. **The Interior or Nucleus.**—Though the mere outside skin of our planet is all with which direct acquaintance can be expected, the irregular distribution of materials beneath the crust may be inferred from the present distribution of land and water, and the observed differences in the amount of deflection of the plumb-line near the sea and near mountain-chains. The fact that the southern hemisphere is almost wholly covered with water, appears only explicable, as already remarked, on the assumption of an excess of density in the mass of that half of the planet. The existence of such a vast sheet of water as that of the Pacific

*Soc. Washington*, xiii. pp. 31-76; and also Rev. O. Fisher, *Phil. Mag.* for July 1886, and xxxvii. (1894), p. 375, also his 'Physics of the Earth's Crust,' chap. xv.; and the paper by Major Burrard, cited *ante*, p. 20.

Ocean is to be accounted for, says Archdeacon Pratt, by the presence of "some excess of matter in the solid parts of the earth between the Pacific Ocean and the earth's centre, which retains the water in its place, otherwise the ocean would flow away to the other parts of the earth."[1] The same writer points out that a deflection of the plumb-line towards the sea, which has in a number of cases been observed, indicates that "the density of the crust beneath the mountains must be less than that below the plains, and still less than that below the ocean-bed."[2] Apart, therefore, from the depressions of the earth's surface, in which the oceans lie, we must regard the internal density, whether of crust or nucleus, to be somewhat irregularly arranged,—there being an excess of heavy materials in the water-hemisphere and beneath the ocean-beds as compared with the continental masses.

As already stated, it has been argued from the difference between the specific gravity of the whole globe and that of the crust, that the interior must consist of heavier material, and may be metallic. The effect of the enormous internal pressure might be supposed to make the density of the nucleus much higher, even if the interior consisted of matter which, on the surface, would be no heavier than that of the crust, and an argument might be maintained for the probable comparative lightness of the substance composing the nucleus. That the total density of the planet does not greatly exceed its observed amount, may indicate that some antagonistic force counteracts the effect of pressure. The only force we can suppose capable of so acting is heat. It must be admitted that we have still much to learn respecting the laws that regulate the compression of solids, liquids, and gases under such vast pressures as must exist within the earth's interior. Even with the comparatively feeble pressures attainable in our physical laboratories, gases and vapours can be compressed into liquids, sometimes even into solids, and in the liquid condition another law of compressibility appears to begin. We know also from experiment that some substances have their melting-point raised by pressure.[3] It may be argued that the same effect takes place within the earth; that pressure increasing inward to the centre of the globe, while augmenting the density of each successive shell, may retain the whole in a practically solid condition, yet at temperatures far above the normal melting-points at the surface. The difference between the density of the whole globe and that of the crust might on this view of the subject be due to pressure, rather than to any essential difference of composition. Laplace proposed the hypothesis that the increase of the square of the density is proportional to the increase of the pressure, which gives a density of 8·23 at half the terrestrial radius and of

[1] 'Figure of the Earth,' 4th edit. p. 236.

[2] *Op. cit.* p. 200. See also Herschel, 'Phys. Geog.' § 13. O. Fisher, *Cambridge Phil. Trans.* xii. part ii.; 'Physics of the Earth's Crust,' p. 124; and *Phil. Mag.* July 1886. Faye, *Comptes rendus*, cii. (1886), p. 651.

[3] Under a pressure of 792 atmospheres, spermaceti has its melting-point raised from 51° to 80·2°, and wax from 64·5° to 80·2°.

10·74 at the centre. From another law proposed by Professor Darwin, the density at half the radius is only 7·4, but thence towards the centre increases rapidly up to infinity.[1] Dr. Pfaff has stated that the mean terrestrial density of 5·5 may not be incompatible with the notion that the whole globe consists of materials of the same density as the rocks of the crust.[2] The following table by Mr. R. S. Woodward combines the calculations as to the distribution of density and pressure between the earth's surface and centre :—

VARIATION OF TERRESTRIAL DENSITY, GRAVITY, AND PRESSURE ACCORDING TO THE LAPLACIAN LAW.

| Depth in Miles. | Density. | Acceleration of Gravity. | Pressure in Atmospheres. | Pressure in Pounds per Square Inch. |
|---|---|---|---|---|
| 0 | 2·75 | 1·0000g | 1 | 15 |
| 1 | . | ... | 400 | 6,000 |
| 2 | . . | ... | 800 | 12,000 |
| 3 | . . | . | 1,210 | 18,150 |
| 4 | .. | ... | 1,620 | 24,300 |
| 5 | 2·76 | 1·0006g | 2,020 | 30,300 |
| 10 | 2·78 | 1·0012g | 4,200 | 63,000 |
| 15 | 2·79 | 1·0018g | 6,390 | 95,850 |
| 20 | 2·81 | 1·0024g | 8,600 | 129,000 |
| 50 | 2·89 | 1·0060g | 22,000 | 330,000 |
| 100 | 3·03 | 1·0116g | 45,300 | 679,500 |
| 500 | 4·18 | 1·0379g | 236,000 | 3,540,000 |
| 560 | 4·36 | 1·0389g | 318,000 | 4,770,000 |
| 610 | 4·50 | 1·0392g[3] | 354,000 | 5,310,000 |
| 660 | 4·65 | 1·0389g | 391,000 | 5,865,000 |
| 1000 | 5·63 | 1·0225g | 672,000 | 10,080,000 |
| 2000 | 8·28 | 0·8312g | 1,700,000 | 25,500,000 |
| 3000 | 10·12 | 0·4567g | 2,640,000 | 39,600,000 |
| 3950 | 10·74 | 0·0000g | 3,000,000 | 45,000,000 |

Analogies in the solar system, as well as the actual structure of the rocky crust of the globe, suggest that heavier metallic ingredients possibly predominate in the nucleus. If the materials of the globe were once in a liquid condition, they would then doubtless be subject to internal arrangement in accordance with their relative specific gravities. We may conceive that there would be, so long as internal mobility lasted, a tendency in the denser elements of our planet to gravitate towards the centre, in the lighter to accumulate outside. That a distribution of this nature has certainly taken place to some extent, is evident from the structure of the envelopes and crust. It is what might be expected, if the constitution of

[1] See the calculations and comparison of the two laws given by the Rev. O. Fisher, 'Physics of the Earth's Crust,' 2nd edit. chap. ii. Legendre supposed that the density being 2·5 at the surface, it is 8·5 at half the length of the radius and 11·3 at the centre. More recently E. Roche calculated these densities to be 2·1, 8·5, and 10·6 respectively.

[2] 'Allgemeine Geologie als exacte Wissenschaft,' p. 42.

[3] This is the maximum value, and the corresponding depth, 610 miles, is the depth at which a given mass would have the greatest weight. *13th Ann. Rep. U.S. Geol. Survey*, 1894, p. 236. See also Mr. C. S. Schlichter, "Note on the Pressure within the Earth," *Journ. Geol.* vi. (1898), p. 65.

the globe resembles, on a small scale, the larger planetary system of which it forms a part. But before proceeding further in the discussion of the probable nature and condition of the interior, we may with advantage consider the evidence that is available from actual observation regarding the temperature of that interior.

Evidence of Internal Heat.—In the evidence obtainable as to the former history of the earth, no fact is of more importance than the existence of a high temperature beneath the crust, which has now been placed beyond all doubt. This feature of the planet's organisation is made clear by the following proofs:—[1]

(1) *Volcanoes.*—In many regions of the earth's surface, openings exist from which steam and hot vapours, ashes and streams of molten rock, are from time to time emitted. The abundance and wide diffusion of these openings, inexplicable by any mere local causes, must be regarded as indicative of a very high internal temperature. If to the still active vents of eruption we add those which have formerly been the channels of communication between the interior and the surface, there are perhaps few large regions of the globe where proofs of volcanic action cannot be found. Everywhere we meet with masses of molten rock which have risen from below, as if from some general reservoir. The phenomena of active volcanoes are fully discussed in Book III. Part I.

(2) *Hot Springs.*—Where volcanic eruptions have ceased, evidence of a high internal temperature is still often to be found in springs of hot water which continue for centuries to maintain their heat. Thermal springs, however, are not confined to volcanic districts. They sometimes rise even in regions many hundreds of miles distant from any active volcanic vent. The hot springs of Bath (temp. 120° Fahr.) and Buxton (temp. 82° Fahr.) in England are fully 900 miles from the Icelandic volcanoes on the one side, and 1100 miles from those of Italy and Sicily on the other.

(3) *Borings, Wells, Mines, and Deep Tunnels.*—The influence of the seasonal changes of temperature extends downward from the surface to a depth which varies with latitude, with the thermal conductivity of soil and rocks, and perhaps with other causes. The cold of winter and the heat of summer may be regarded as following each other in successive waves downward, until they disappear along a limit at which the temperature remains constant. This zone of invariable temperature is commonly believed to lie at a depth of somewhere between 60 and 80 feet in temperate regions. At Yakutsk in Eastern Siberia (lat. 62° N.), however, as shown in a well-sinking, the soil is permanently frozen to a depth of rather more than 600 feet, where fluid water is reached.[2] In Java, on

[1] A good general account of this subject will be found in E. Dunker's 'Ueber die Wärme im Inneren der Erde,' Stuttgart, 1896, pp. x, 242. The author supplies information regarding the most important borings and mine observations up to the time of his writing. Another useful digest of the facts will be found in Günther's 'Handbuch der Geophysik,' 2nd edit. vol. i. pp. 328-343.

[2] Von Middendorff, 'Reise in den äussersten Norden und Osten Sibiriens,' St. Petersburg, 1848. Helmersen, *Brit. Assoc. Rep.* 1871, p. 22. See vol. for 1886, p. 271.

the other hand, a constant temperature is said to be met with at a depth of only 2 or 3 feet.[1]

It is a remarkable fact, now verified by observation all over the world, that below the limit of the influence of ordinary seasonal changes the temperature, so far as we yet know, is nowhere found to diminish downwards. It always rises; and its rate of increment seldom falls much below a general average. The most exceptional cases occur under circumstances not difficult of explanation. On the one hand, the neighbourhood of hot-springs, of large masses of lava, or of other manifestations of volcanic activity, may raise the subterranean temperature much above its normal condition; and this augmentation may not disappear for many thousand years after the volcanic activity has wholly ceased, since the cooling down of a subterranean mass of lava must necessarily be a very slow process. Lord Kelvin has even proposed to estimate the age of subterranean masses of intrusive lava from their excess of temperature above the normal amount for their isogeotherms (lines of equal earth-temperature), some probable initial temperature and rate of cooling being assumed. On the other hand, the spread of a thick mass of snow and ice over any considerable area of the earth's surface, and its continuance there for several thousand years, would so depress the isogeotherms that, for many centuries afterwards, there would be a fall of temperature for a certain distance downwards. At the present day, in the more northerly parts of the northern hemisphere, there are such evidences of a former more rigorous climate, as in the well-sinking at Yakutsk just referred to.[2] A line, north of which the ground beneath the surface is permanently frozen, can be traced across Northern Russia by Tobolsk to Tomsk, thence eastward by Lake Baïkal to the Sea of Okhotsk, and across Alaska and Canada south of the Great Slave Lake and Lake Winnipeg to the eastern coast of Labrador.[3] Lord Kelvin has calculated that any considerable area of the earth's surface covered for several thousand years by snow or ice, and retaining, after the disappearance of that frozen covering, an average surface temperature of 13° C., "would during 900 years show a decreasing temperature for some depth down from the surface, and 3600 years after the clearing away of the ice would still show residual effect of the ancient cold, in a half rate of augmentation of temperature downwards in the upper strata, gradually increasing to the whole normal rate, which would be sensibly reached at a depth of 600 metres."[4]

This exceptional depth of frozen soil is probably connected with the former continuance of the Ice Age referred to in the next paragraph.

[1] Junghuhn's 'Java,' ii. p. 771.

[2] Professor Prestwich (*Inaugural Lecture*, 1875, p. 45) suggested that to the more rapid refrigeration of the earth's surface during this cold period, and to the consequent depression of the subterranean isothermal lines, the alleged present comparative quietude of the volcanic forces is to be attributed, the internal heat not having yet recovered its dominion in the outer crust. See his 'Collected Papers on some Controverted Questions in Geology,' p. 159; also Mr. C. Davison, *Geol. Mag.* 1895, p. 356; and Rev. O. Fisher, *Phil Mag.* July 1899, p. 134; Harboe, *Z. D. G. G.* l. (1898), p. 441, and li. (1899), pp. 322, 526.

[3] Peschel-Leipoldt, 'Physische Erdkunde,' Leipzig, 1879, Band i. p. 185.

[4] *Brit. Assoc. Reports*, 1876, Sections, p. 3.

Beneath the limit to which the influence of the changes of the seasons extends, observations all over the globe, and at many different elevations, give an increase of temperature downwards, or "temperature gradient," the computation of its rate being based especially on observations in deep mines and borings. Professor Prestwich concluded, from a large series of observations collated by him, that the average increment might be 1° Fahr. for every 47·5 feet.[1] Observations taken in the extraordinarily deep boring at Schladebach, near Dürrenberg, showed that in a depth of 5736 feet the average rise of temperature was 1° Fahr. for every 65 feet.[2] According to data collected by a Committee of the British Association, the average gradient appears to be 1° Fahr. for every 64 feet, or $\frac{1}{64}$th of a degree per foot.

Isogeotherms near the surface follow approximately the contours of the surface, but are flatter than these, and "their flattening increases as we pass to lower ones, until at a considerable depth they become sensibly horizontal planes. The temperature gradient is consequently steepest beneath gorges and least steep beneath ridges."[3]

While there is everywhere a progressive increase of temperature downwards, its rate is by no means uniform. In the frozen soil of Yakutsk the increase amounted to as much as 1° Fahr. for every 28 feet.[4] On the other hand, the lowest rate yet recorded appears to be that reported by Professor A. Agassiz, from Calumet, Michigan, where, down to a depth of 4712 feet, the rate of augmentation was found to be on an average 1° Fahr. for every 223·7 feet.[5] The more detailed observations which have been made in recent years have likewise brought to light the important fact that considerable variations in the rate of increase take place even in the same bore. The temperatures obtained at different depths in the Rose Bridge colliery shaft, Wigan, for instance, read as in the following columns :—

| Depth in Yards. | Temperature (Fahr.) | Depth in Yards. | Temperature (Fahr.) |
|---|---|---|---|
| 558 | 78 | 663 | 85 |
| 605 | 80 | 671 | 86 |
| 630 | 83 | 679 | 87 |

[1] *Proc. Roy. Soc.* xli. (1885), p. 55.

[2] *Brit. Assoc. Rep.* 1889, "Report of Underground Temperature Committee."

[3] J. D. Everett, *Brit. Assoc. Rep.* 1879, Sections, p. 345. Compare also the elaborate observations made in the St. Gothard Tunnel, F. Stapff, 'Rapports, Conseil Féd. St. Gothard,' vol. viii., and 'Geologische Durchschnitte des Gothard Tunnels'; "Étude de l'Influence de la Chaleur de l'Intérieur de la Terre," etc., *Revue Univ. Mines*, 1879-80. *Min. Proc. N. England Inst. Mining-Mechan. Engin.* xxxii. (1883), p. 19. "Reports of Committee on Underground Temperature," *Brit. Assoc. Rep.* from 1868 onwards, with summary of results in the volume for 1882. A voluminous and valuable collection of data bearing on this subject was compiled by Professor Prestwich and published in *Proc. Roy. Soc.* xli. (1885), p. 1. A revised edition of this paper will be found in his 'Controverted Questions in Geology,' pp. 166-279.

[4] Mr. Fisher has suggested that this exceptional rapidity may be due to the low value of the conductivity of ice ('Physics of the Earth's Crust,' p. 7).

[5] *Amer. Journ. Sci.* Dec. 1895.

| Depth in Yards. | Temperature (Fahr.) | Depth in Yards. | Temperature (Fahr.) |
|---|---|---|---|
| 734 | 88½ | 783 | 92 |
| 745 | 89 | 800 | 93 |
| 761 | 90½ | 806 | 93½ |
| 775 | 91½ | 815 | 94 |

At La Chapelle, in an important well made for the water-supply of Paris, observations have been taken of the temperature at different depths, as shown in the subjoined table :—[1]

| Depth in Metres. | Temperature (Fahr.) | Depth in Metres. | Temperature (Fahr.) |
|---|---|---|---|
| 100 | 59·5 | 500 | 72·6 |
| 200 | 61·8 | 600 | 75·0 |
| 300 | 65·5 | 660 | 76·0 |
| 400 | 69·0 | | |

In drawing attention to the foregoing temperature-observations at the Rose Bridge colliery—the deepest mine in Great Britain—Professor Everett points out that, assuming the surface temperature to be 49° Fahr., in the first 558 yards the rate of rise of temperature is 1° for 57·7 feet; in the next 257 yards it is 1° in 48·2 feet; in the portion between 605 and 671 yards—a distance of only 198 feet—it is 1° in 33 feet; in the lowest portion of 432 feet it is 1° in 54 feet.[2] When such irregularities occur in the same vertical shaft, it is not surprising that the average should vary so much in different places.

There can be little doubt that one cause of these variations is to be sought in the different thermal conductivities of the rocks of the earth's crust. The first accurate measurements of the conducting powers of rocks were made by the late J. D. Forbes at Edinburgh (1837-45). He selected three sites for his thermometers, one in "trap-rock" (an andesite of Lower Carboniferous age), one in loose sand, and one in sandstone, each set of instruments being sunk to depths of 3, 6, 12, and 24 French feet from the surface. He found that the wave of summer heat reached the bulb of the deepest instrument (24 feet) on 4th January in the trap-rock, on 25th December in the sand, and on 3rd November in the sandstone, the trap-rock being the worst conductor and the solid sandstone by far the best.[3]

As a rule, the lighter and more porous rocks offer the greatest resistance to the passage of heat, while the more dense and crystalline offer the least resistance. The resistance of opaque white quartz is expressed by the number 114, that of basalt stands at 273, while that of cannel coal stands very much higher at 1538, or more than thirteen times that of quartz.[4]

[1] *Brit. Assoc. Rep.* 1873, Sections, p. 254.

[2] *Ibid.* 1870, Sections, p. 31. See a paper by Professor Sollas, *Geol. Mag.* 1901, p. 502.

[3] *Trans. Roy. Soc. Edin.* xvi. p. 211.

[4] Herschel and Lebour (British Association Committee on Thermal Conductivities of Rocks). *Brit. Assoc. Rep.* 1875, p. 58. The final Report is in the vol. for 1881.

It is evident, also, from the texture and structure of most rocks, that the conductivity must vary in different directions through the same mass, heat being more easily conducted along than across the "grain," the bedding, and the other numerous divisional surfaces. Experiments have been made to determine these variations in a number of rocks. Thus, the conductivity in a direction transverse to the divisional planes being taken as unity, the conductivity parallel with these planes was found in a variety of magnesian schist to be 4·028. In certain slates and schistose rocks from Central France, the ratio varied from 1 : 2·56 to 1 : 3·952 Hence, in such fissile rocks as slate and mica-schist, heat may travel four times more easily along the planes of cleavage or foliation than across them.[1]

In reasoning upon the discrepancies in the rate of increase of subterranean temperatures, we must also bear in mind that convection by percolating streams of water must materially affect the transference of heat from below.[2] Certain kinds of rock are more liable than others to be charged with water, and in almost every boring or shaft one or more horizons of such water-bearing rocks are met with. The effect of interstitial water is to diminish thermal resistance. Dry red brick has its resistance lowered from 680 to 405 by being thoroughly soaked in water, its conductivity being thus increased 68 per cent. A piece of sandstone has its conductivity heightened to the extent of 8 per cent by being wetted.[3]

Mallet contended that the variations in the amount of increase in subterranean temperature are too great to permit us to believe them to be due merely to differences in the transmission of the general internal heat, and that they point to local accessions of heat arising from transformation of the mechanical work of compression, which is due to the constant cooling and contraction of the globe.[4] But while the cause adduced by him may undoubtedly be effective, we may nevertheless hold that the observed variations do not appear to be greater than, from the known diversities in the conductivities of rocks and the influence of circulating water, they might fairly be expected to be.

While it may be affirmed that within the superficial part of the terrestrial crust, as far down as it has been pierced, a general rise of temperature amounting to 1° Fahr. for every 50 or 60 feet of descent has

[1] "Report of Committee on Thermal Conductivities of Rock," *Brit. Assoc. Rep.* 1875, p. 61. Jannettaz, *B. S. G. F.* (April-June, 1874), ii. p. 264. This observer has carried out a series of detailed researches on the propagation of heat through rocks, which will be found in *B. S. G. F.*, tomes i.-ix. (3rd series). See also the paper by Lord Kelvin and Mr. Erskine Murray, "On the Temperature Variation of the Thermal Conductivity of Rocks" (*Nature*, lii. 1895, p. 182), where a series of experiments is recorded, having for their object to find the temperature variation of thermal conductivity of slate and granite. The results arrived at were questioned by Professor R. Weber, *op. cit.* p. 458.

[2] In the great bore of Sperenberg (4172 feet, entirely in rock-salt, except the first 283 feet) there is evidence that the water near the top is warmed 4½° Fahr. by convection. *Brit. Assoc. Rep.* 1882, p. 78.

[3] Herschel and Lebour, *Brit. Assoc. Rep.* 1875, p. 58.

[4] "Volcanic Energy," *Phil. Trans.* 1875.

been definitely proved, it by no means follows that this rate continues inward to the centre of the earth. Lord Kelvin, indeed, has computed that if the rate of increase of temperature is taken to be 1° for every 51 feet for the first 100,000 feet, it will begin to diminish below that limit, being only 1° in 2550 feet at 800,000 feet, and then rapidly lessening.[1]

Probable Condition of the Earth's Interior.—Various theories have been propounded on this subject. There are only three which merit serious consideration. (1) One of these supposes the planet to consist of a solid crust and a molten interior. (2) The second holds that, with the exception of local vesicular spaces, the globe is solid and rigid to the centre. (3) The third contends that beneath the crust and the molten magma that underlies it, the interior is mainly filled with gas under enormous pressure and high temperature, and that from this gaseous nucleus a perfect gradation exists into the solid, rigid rock that forms the crust.

1. *The arguments in favour of internal liquidity* may be summed up as follows:—(*a*) The ascertained rise of temperature inwards from the surface is such that, at a very moderate depth, the ordinary melting-point of even the most refractory substances would be reached. At 20 miles the temperature, if it increases progressively, as it does in the depths accessible to observation, must be about 1760° Fahr.; at 50 miles it must be 4600°, or far higher than the fusing-point even of so stubborn a metal as platinum, which melts at 3080° Fahr. (*b*) All over the world volcanoes exist from which steam and torrents of molten lava are from time to time erupted. Abundant as are the active volcanic vents, they form but a small proportion of the whole which have been in operation since early geological time. It has been inferred, therefore, that these numerous funnels of communication with the heated interior could not have existed and poured forth such a vast amount of molten rock, unless they drew their supplies from an immense internal molten nucleus. (*c*) When the products of volcanic action from different and widely separated regions are compared and analysed, they are found to exhibit a general uniformity of character. Lavas from Vesuvius, from Hecla, from the Andes, from Japan, and from New Zealand present such an agreement in essential particulars as, it is contended, can only be accounted for on the supposition that they have all emanated from one vast common source.[2] (*d*) The abundant earthquake-shocks which affect large areas of the globe are maintained to be inexplicable unless on the supposition of the existence of a thin and somewhat flexible crust. (*e*) The universal proofs that the sea-floor has been elevated into land, and that thick marine sedimentary formations have been folded, crumpled, and pushed over each other, are regarded as evidence that such a crust exists, that it is of no great thickness, and that it rests upon a viscous or liquid interior.[3]

[1] *Trans. Roy. Soc. Edin.* xxiii. p. 163.

[2] See D. Forbes, *Popular Science Review*, April 1869.

[3] The arguments for a comparatively thin crust resting on viscous or liquid material below are fully given by the late Sir Joseph Prestwich in his paper read to the Royal Society

These arguments, it will be observed, are inferences drawn from observations of the present constitution of the globe. They are based on geological data, and have been frequently and strongly urged by geologists as supporting the only view of the nature of the earth's interior supposed by them to be compatible with geological evidence. Before the question was attacked on physical grounds, geologists were generally in the habit of believing that the crust of the earth was a mere thin shell which from time to time, owing to the diminution of volume caused by cooling and contraction, settled down upon the nucleus and adjusted itself to the loss of superficies by undergoing such plication as is more especially conspicuous in the structure of mountains; that the vast mass of the interior was in an intensely hot and even molten condition; and that by this structure the geological phenomena above referred to received their simplest explanation. When the physicists brought forward and pressed their deductions as to the rigidity of the earth, their arguments appeared so weighty that many geologists, with some reluctance, accepted them, though they seemed to make the interpretation of the structure of the terrestrial crust more difficult than ever. Among the attempts to reconcile the physical and geological difficulties the most notable was made in the hypothesis of "a rigid nucleus nearly approaching the size of the whole globe, covered by a fluid substratum of no great thickness, compared with the radius, upon which a crust of lesser density floats in a state of equilibrium."[1] The nucleus was assumed to owe its solidity to "the enormous pressure of the superincumbent matter, while the crust owes its solidity to having become cool. The fluid substratum is not under sufficient pressure to be rendered solid, and is sufficiently hot to be fluid, being probably more viscous in its lower portion through pressure, and likewise passing into a viscous state in its upper parts through cooling, until it joins the crust."[2] The contraction and consolidation of this substratum were assumed as the explanation of the plication which the crust has certainly undergone.

The question has been attacked with renewed energy from the physical side. The conception of an outer thin terrestrial shell resting upon a liquid or viscous substratum is especially enforced in a modified form by Mr. Fisher. Holding that the globe was once probably entirely melted,

(*Proc. Roy. Soc.* xli. 1888, p. 156), and reprinted in his 'Controverted Questions in Geology,' p. 147; see also his 'Geology: Chemical, Physical, and Stratigraphical,' vol. ii. p. 539. It should be noted, however, that the doctrine of internal fluidity was questioned by Lyell, who imagined that volcanic action was connected with local tracts of melted matter in the earth's crust which were in some way produced or kept up by the passage of an electro-magnetic force from the sun to our globe ('Principles of Geology,' 10th edit. pp. 211, 232).

[1] See Dana in *Silliman's Journal*, iii. (1847), p. 147; *Amer. Journ. Sci.* 1873. The hypothesis of a fluid substratum has been advocated by Shaler, *Proc. Bost. Nat. Hist. Soc.* xi. (1868), p. 8; *Geol. Mag.* v. p. 511. J. Le Conte, *Amer. Journ. Sci.* 1872, 1873. O. Fisher, *Geol. Mag.* v. (new series), pp. 291, 551; 'Physics of the Earth's Crust,' 1st edit. 1883. Prestwich, 'Controverted Questions in Geology,' p. 147. Hill, *Geol. Mag.* v. (new series), pp. 262, 479. The idea of a viscous layer between the solidifying central mass and the crust was present in Hopkins' mind. *Brit. Assoc.* 1848, Reports, p. 48.

[2] See Mr. Fisher's first edition of his book, p. 269. The hypothesis, as thus stated, was afterwards abandoned by him as untenable (2nd edit. 1889, p. 54).

he points out that while the argument in favour of rigidity drawn from the phenomena of precession has been abandoned by the leading physicists, that based on the tides is unsatisfactory as proving too much. He thinks that the available evidence points to the existence of a crust which may have an average thickness of 25 miles, and that beneath it lies a substratum of fused rock possibly saturated with water-gas far above the critical temperature, the compressibility of which would account for the absence of measurable tides in the interior of the planet and thus remove the principal argument for rigidity. He comes to the conclusion that the substratum is not an inert mass, but is traversed by convection currents, and must therefore be not merely viscous but actually liquid, from time to time melting off portions of the overlying crust.[1]

2. *The arguments in favour of the internal solidity of the earth* are based on physical and astronomical considerations, and may be arranged as follows:—

(*a*) Argument from precession and nutation.—The problem of the internal condition of the globe was attacked as far back as the year 1839 by Hopkins, who calculated how far the planetary motions of precession and nutation would be influenced by the solidity or liquidity of the earth's interior. He found that the precessional and nutational movements could not possibly be as they are, if the planet consisted of a central core of molten rock surrounded with a crust of twenty or thirty miles in thickness; that the least possible thickness of crust consistent with the existing movements was from 800 to 1000 miles; and that the whole might even be solid to the centre, with the exception of comparatively small vesicular spaces filled with melted rock.[2]

M. Delaunay[3] threw doubt on Hopkins' views, and suggested that, if the interior were a mass of sufficient viscosity, it might behave as if it were a solid, and thus the phenomena of precession and nutation might not be affected. Lord Kelvin, who had already arrived at the conclusion that the interior of the globe must be solid, and acquiesced generally in Hopkins' conclusions, remarked that the hypothesis of a viscous and quasi-rigid interior "breaks down when tested by a simple calculation of the amount of tangential force required to give to any globular portion of the interior mass the precessional and nutational motions which, with other physical astronomers, M. Delaunay attributes to the earth as a whole."[4] He held the earth's crust down to depths of hundreds of kilometres to be capable of resisting such a tangential stress (amounting to nearly $\frac{1}{10}$th of a gramme weight per square centimetre) as would

[1] *Op. cit.* pp. 22, 41, 178.

[2] *Phil. Trans.* 1839, p. 381; 1840, p. 193; 1842, p. 43; *Brit. Assoc.* 1847.

[3] In a paper on the hypothesis of the interior fluidity of the globe, *Comptes rendus*, July 13, 1868; *Geol. Mag.* v. p. 507. See H. Hennessy, *Comptes rendus*, March 6, 1871; *Geol. Mag.* viii. p. 216; *Nature*, xv. p. 78; *Phil. Mag.* xxii. Sept. and Oct. 1886, pp. 233-257, 328-331. In this paper he adheres to his view that the earth's interior cannot be solid to the centre, but consists of a shell inside of which lies a mass of viscous matter, the whole rotating practically as one solid mass. O. Fisher, 'Physics of the Earth's Crust,' 2nd edit. 1889.

[4] *Nature*, Feb. 1, 1872.

with great rapidity draw out of shape any plastic substance which could properly be termed a viscous fluid, and he concluded "that the rigidity of the earth's interior substance could not be less than a millionth of the rigidity of glass without very sensibly augmenting the lunar nineteen-yearly nutation."[1]

In Hopkins' hypothesis he assumed the crust to be infinitely rigid and unyielding, which is not true of any material substance. Lord Kelvin subsequently returning to the problem, in the light of his own researches in vortex-motion, found that, while the argument against a thin crust and vast liquid interior is still invincible, the phenomena of precession and nutation do not decisively settle the question of internal fluidity, as Hopkins, and others following him, had believed, though the solar semi-annual and lunar fortnightly nutations absolutely disprove the existence of a thin rigid shell full of liquid. If the inner surface of the crust or shell were rigorously spherical, the interior mass of supposed liquid could experience no precessional or nutational influence, except in so far as, if heterogeneous in composition, it might suffer from external attraction due to non-sphericity of its surfaces of equal density. But "a very slight deviation of the inner surface of the shell from perfect sphericity would suffice, in virtue of the quasi-rigidity due to vortex-motion, to hold back the shell from taking sensibly more precession than it would give to the liquid, and to cause the liquid (homogeneous or heterogeneous) and the shell to have sensibly the same precessional motion as if the whole constituted one rigid body."[2] The problem presented by the precession of a viscous spheroid has been discussed by Professor George Darwin, who arrives at results nearly the same as those announced by Lord Kelvin regarding the slight difference between the precession of a fluid and a rigid spheroid.[3]

It is affirmed that the assumed comparatively thin crust surrounding a vast liquid interior must have such perfect rigidity as is possessed by no known substance. The tide-producing force of the moon and sun exerts such a strain upon the substance of the globe, that it seems in the highest degree improbable that the planet could maintain its shape as it does unless the supposed crust were at least 2000 or 2500 miles in thickness.[4] That the solid mass of the earth must yield to this strain is certain, though the amount of deformation is so slight as to have hitherto escaped all attempts to detect it.[5] Had the rigidity been even that of glass or of steel, the deformation would probably have been by this time observed, and the actual phenomena of precession and nutation, as well as of the tides, would then have been very sensibly diminished.[6] The conclusion was thus reached by Lord Kelvin that the

[1] *Loc. cit.* p. 258.

[2] Lord Kelvin, *Brit. Assoc. Rep.* 1876, Sections, p. 5. Thomson and Tait, 'Natural Philosophy,' 1883, art. 847.

[3] *Phil. Trans.* 1879, part ii. p. 464. *Nature*, 2nd Nov. 1882.

[4] Lord Kelvin, *Proc. Roy. Soc.* April 1862.

[5] See *Association Française pour l'Avancement des Sciences*, v. p. 281.

[6] Lord Kelvin, *loc. cit.*

mass of the earth "is on the whole more rigid certainly than a continuous solid globe of glass of the same diameter."[1]

This result has been supported by the computations of other physicists and mathematicians. Besides those of Professor Darwin, reference may here be made to the work of Professor S. Newcomb, who, calculating the rigidity of the earth from the 427 days' period of the variations of latitude, estimated it to be rather above that of steel.[2] Mr. P. Rudski of Odessa afterwards went over the computations in more detail and arrived at the conclusion that the coefficient of rigidity of the earth is nearly twice as great as that of steel.[3] There thus appears to be no escape from the deduction that, whatever may be the condition of the substance of the earth's interior, it behaves like an extremely rigid substance.

(*b*) Argument from the tides.—The phenomena of the oceanic tides show that the earth acts as a rigid body, either solid to the centre or possessing so thick a crust (2500 miles or more) as to give to the planet practical solidity. Lord Kelvin remarks that "were the crust of continuous steel and 500 kilometres thick, it would yield very nearly as much as if it were india-rubber to the deforming influences of centrifugal force and of the sun's and moon's attractions." It would yield, indeed, so freely to these attractions "that it would simply carry the waters of the ocean up and down with it, and there would be no sensible tidal rise and fall of water relatively to land."[4] Professor Darwin, in a series of papers, investigated mathematically the bodily tides of viscous and semi-elastic spheroids, and the character of the ocean tides on a yielding nucleus.[5] His results tended to increase the force of Lord Kelvin's argument, that "no very considerable portion of the interior of the earth can even distantly approach the fluid condition," the effective rigidity of the whole globe being very great. Subsequently, however, on renewed investigation, he came to the conclusion that "it is not possible to attain any estimate of the earth's rigidity in this way,"[6] though he still agreed with the view of the effective rigidity of the earth's whole mass.

(*c*) Argument from relative densities of melted and solid rock.—It has been further urged, as an objection to the hypothesis of a thin shell or crust covering a nucleus of molten matter, that cold solid rock is more dense than hot melted rock, and that even if a thin crust were formed over the central molten globe it would immediately break up and the fragments would sink towards the centre.[7] Recent experiments have been cited which show that diabase (of density 3·017) contracts nearly 4 per cent on solidification, and that the resulting

1 *Trans. Roy. Soc. Edin.* xxiii. 157.

2 *Monthly Notices, Astron. Soc.* 1892, p. 336.

3 *Phil. Mag.* xxxviii. (1894), p. 218.

4 *Brit. Assoc. Rep.* 1876, Sections, p. 7.

5 *Phil. Trans.* 1879, part ii. See also *Brit. Assoc. Rep.* 1882, Sections, p. 473.

6 *Proc. Roy. Soc.* Nov. 25, 1886.

7 This objection has been repeatedly urged by Lord Kelvin. See *Trans. Roy. Soc. Edin.* xxiii. p. 157 ; and *Brit. Assoc. Rep.* 1870, Sections, p. 7.

homogeneous glass has a density of only 2·717.[1] Appeal has likewise been made to the behaviour of the crust of cooled rock which forms on the surface of the lava-caldron of Hawaii and from time to time breaks up, when large cakes of it turn over on end and sink down into the surging mass of molten rock. But on examination it will be found that the argument we are now considering does not derive any real support from this observation. The fact that a crust of appreciable thickness can form and remain on the surface of the lava shows that cooling can proceed for some time without any displacement of the lithoid cake, and this cake is rent by the movements of the molten rock and breaks up into separate masses; the fact that these turn over on end and sink points, as Mr. Fisher ingeniously suggests, to their being under the influence of convection currents which draw them down.[2] In the numerous cases where flowing currents of lava have been watched, no proof has been observed that the superficial crust breaks up and sinks into the body of the molten rock.

If the difference between the specific gravity of the interior and that of the visible parts of the crust be due, not merely to the effect of pressure, but to the presence in the interior of intensely heated metallic substances, we cannot suppose that solidified portions of such rocks as granite and the various lavas could ever have sunk into the centre of the earth so as to build up there the honeycombed cavernous mass which might have served as a nucleus in the ultimate solidification of the whole planet. If the earliest formed portions of the comparatively light crust were denser than the underlying liquid, they would no doubt descend until they reached a stratum with specific gravity agreeing with their own, or until they were again melted.[3]

One of the most serious objections entertained by geologists to the hypothesis of the practical solidity of the whole globe arises from the difficulty of comprehending how such a globe could possess the complicated structure which is presented in the terrestrial crust. That structure indicates a capability of yielding to strain such as might be supposed impossible in a globe possessing on the whole the rigidity of steel or glass. But this difficulty may be more formidable in appearance than in reality. The earth must certainly possess such a degree of rigidity as to resist tidal deformation. Professor Darwin has calculated the limiting rigidity in the materials of the earth which is necessary to prevent the weight of mountains and continents from reducing them to the fluid condition or else cracking,

[1] C. Barus, *Phil. Mag.* 1893, p. 174. From a cause merely mechanical, pieces of the original cold rock, though so much denser, float for a time on the melted material. *Ib.* p. 189. It must be remembered, however, that the diabase was originally a molten rock which cooled with exceeding slowness, and ultimately assumed a crystalline condition, whereas the laboratory experiments converted it into a glass. As is well known, the specific gravity of a volcanic glass is lower than that of a rock of the same chemical composition in the crystalline state.

[2] 'Physics of the Earth's Crust,' p. 51.

[3] See D. Forbes, *Geol. Mag.* iv. p. 435. The evidence for the internal solidity of the earth is criticised by Dr. M. E. Wadsworth in the *American Naturalist*, 1884.

and has found that these materials must be as strong as granite 1000 miles below the surface, or else much stronger than granite near the surface.[1] But high rigidity, that is, elasticity of form, is not contradictory of plasticity. Even bodies like steel may, under suitable stress, be made to flow like butter (see *postea*, Book III. Part I. Section iv. § 3). While, therefore, the earth may possess as a whole the rigidity of steel, there seems no reason why, under sufficient strain, the outer portions may not be plicated or even reduced to the fluid condition. It is important "to distinguish viscosity, in which flow is caused by infinitesimal forces, from plasticity, in which permanent distortion or flow only sets in when the stresses exceed a certain limit."[2]

In speculating on the plication of the earth's crust, we ought not to forget that, from the earliest times, the existing continental regions seem to have specially suffered from the efforts of the planet to adjust its external form to its diminishing diameter and lessening rapidity of rotation. They have served as lines of relief from the strain of compression during many successive epochs. It is along their axial lines—their long dominant mountain-ranges—that we should naturally look for evidence of corrugation. Away from these lines of weakness the ground has been upraised for thousands of square miles without plication of the rocks, as in the instructive region of the Western Territories of North America. Nor is there any proof that corrugation, save in ridges and troughs, takes place beneath the great oceanic areas of subsidence.

It appears highly probable that the substance of the earth's interior is at the melting-point proper for the pressure at each depth.[3] Any relief from pressure, therefore, may allow of the liquefaction of the matter so relieved. Such relief is doubtless afforded by the corrugation of mountain-chains and other terrestrial ridges. And it is in these lines of uprise that volcanoes and other manifestations of subterranean heat actually show themselves.

3. *The arguments in favour of the gaseous interior of the earth* have been based on the physico-chemical researches of recent years. The first writer who suggested this view of the structure of our planet appears to have been A. Ritter in a series of "Researches on the Height of the Atmosphere and the Constitution of Gaseous Heavenly Bodies."[4] Arguing from Andrews' observations, which indicated that under high pressures above the critical point, not only in the case of carbonic acid but with regard to all other substances, no difference might any longer exist between the gaseous and liquid states, he thought that we should probably in these inquiries have to deal with only two distinct conditions of aggregation,

[1] *Proc. Roy. Soc.* 1881, p. 432. The crushing strength of granite is 7000 to 22,000 pounds per square inch; that of limestone 11,000 to 25,000; that of sandstone 6000 to 14,000 (Mr. B. Willis, *18th Ann. Rep. U.S. Geol. Survey*, p. 237). These limits are reached at depths of from 1 to 5 miles.

[2] Professor Darwin in a letter to the author, 9th January 1884.

[3] P. G. Tait, 'Heat,' 1884, p. 123.

[4] *Wiedemann's Annalen der Physik und Chemie*, v. (1878), pp. 405, 543; vi. (1879), p. 135; vii. (1879), p. 304; viii. (1879), p. 157.

the gaseous and the solid, and thus reach the conclusion that the earth consists of a gaseous centre surrounded with a solid crust. If we make the further assumption that, as in the case of water-vapour, dissociation of all other chemical compounds takes place, we may infer that in the central part of the gaseous nucleus the different chemical elements exist next each other in an isolated condition, while farther outwards in the dissociation zone they alternately enter into chemical union and again separate from each other.[1]

The subject has been more recently discussed by the Swedish physicist Professor S. Arrhenius,[2] who treats it in the light of the latest researches on the behaviour of bodies, gaseous, liquid, and solid, under enormous pressures and at high temperatures. He points out that in fluids at high temperatures, where no increase of volume takes place, the internal friction rises with the temperature, or, in other words, the fluidity diminishes; that in gases also a similar effect is observable; and that although gases have the highest and solid bodies the lowest compressibility, nevertheless when a gas near its critical temperature passes into a liquid, through a trifling physical change, the compressibility remains almost unaltered. The higher the pressure, the smaller is the compressibility. Iron or lava in the gaseous form at a depth of 1000 kilometres or more beneath the earth's surface would be more incompressible than steel is above ground.

When, therefore, the Swedish professor continues, we speak of gases at such high temperatures and pressures as those that prevail in the earth's interior, we must conceive of something wholly different from what we ordinarily understand by gas. The density, compressibility and viscosity of such a substance are of such a high order that we might regard it as a solid body, if its true nature were not apparent.[3] In regard to the probable structure of the earth, we may infer that, as at a depth of 40 kilometres (about 25 English miles) the temperature reaches as much as 1200° C. and the pressure amounts to 10,840 atmospheres, most ordinary minerals will become fluid, and the earth's substance at that depth must exist in a molten condition, forming what is known as the magma—an exceedingly viscous and little compressible liquid. This condition, however, cannot extend far inward, for at a depth of some 300 kilometres (186 miles) the temperature is undoubtedly so high as to be beyond the critical temperature of every known substance. The liquid magma thus passes over continuously into a gaseous

[1] *Op. cit.* v. pp. 424, 425.

[2] "Zur Physik des Vulcanismus," *Geol. Fören. i Stockholm Förhandl.* xxii. (1900), pp. 395-419.

[3] If the ordinary gaseous law of density in simple proportion to pressure for the same temperatures holds good, the density of a gaseous orb like the sun will be at the centre about 22·5 times the mean density of the whole, and the material will be nearly one-third denser than the metal platinum. But the general opinion is that this law does not hold beyond a certain limit, above which the density of the gas cannot be increased by any pressure however great. But we are still "ignorant of the laws of pressure, density, and temperature, even for known kinds of matter, at very great pressures and very high temperatures." See Lord Kelvin's 'Popular Lectures and Addresses,' i. pp. 406-408.

magma, of which the viscosity and compressibility should be still greater than in the liquid magma.

"If the rocks at the earth's surface have a density half that of the globe as a whole, and if this density continues to hold good for the magma that arises from the melting of these rocks, we must conceive the existence of a much denser substance in the earth's interior. On various grounds, such as the preponderance of iron in nature, both in meteorites and in the sun, and the phenomena of terrestrial magnetism, it may be inferred that this substance is metallic iron. In consequence of its greater density this iron will naturally lie deeper than the rock-magma, and on account of the high temperature must exist in a gaseous condition. Somewhere about a half of the planet therefore should consequently consist of iron, and of other metals mingled with it in smaller proportions. The semi-diameter of this gaseous iron-sphere will thus include about 80 per cent of the earth's semi-diameter. Then will come about 15 per cent of the gaseous rock-magma, next to it the liquid rock-magma for a thickness of about 4 per cent of the terrestrial semi-diameter, and lastly the solid crust, for which not more than about 1 per cent may be claimed."[1]

This view of the constitution of the earth's interior receives, according to Professor Arrhenius, the most remarkable confirmation from the latest and most precise instrumental observations of earthquake movements. These observations, he thinks, furnish remarkably strong evidence that the earth's interior cannot be solid. "The density of much the largest part (reckoned linearly) of this interior, amounting, as above stated, to about 80 per cent of the radius, must be nearly three times higher than that of quartz. Since now the mean velocity of transmission of the earthquake wave in the interior of the earth has been ascertained to amount to 11·3 kilometres per second, the compressibility of that region must be 31 times less than that of quartz, that is, eight times less than that of solid steel, according to Voigt. This is a figure of precisely that order of magnitude which was to be expected. We may well believe that at depths of more than 1000 kilometres the compressibility of gaseous iron sinks down to some ten times less than that of steel.

"The interior of the earth, therefore, with the exception of a solid crust about 40 kilometres thick, consists of a molten magma 100 or 200 kilometres in depth which shades continuously inward into a gaseous centre. The liquids and gases in the interior possess a viscosity and incompressibility such as permit them to be regarded as solid bodies. From these, however, they are distinguished in the first place by the fact that differentiations are possible to a considerable degree, the effects of which may long endure. In the second place, long-continued pressures, when acting on a large enough scale, may produce great deformations. Further, the liquids must possess the property of great expansion on a diminution of the high pressure, thereby readily becoming fluid. The process must thus differ but little from a normal melting with increase

[1] *Op. cit.* pp. 404, 405.

of volume, and especially of fluidity, as well as with absorption of heat. And yet the condition of aggregation is not thereby altered."[1]

The aspect thus presented of the probable constitution of the interior of our planet appears to accord well with the geological requirements. Not only does it furnish an explanation of the characteristics of earthquake movements, but, as Professor Arrhenius cogently shows, it helps us to understand some of the more difficult problems of volcanic action. It will therefore be further referred to in Book III. Part I. Again, with reference to the crust of the earth, it meets the constantly repeated objections of the geologists to whom the existence of a comparatively thin crust has always seemed an essential condition for the production of that crumpled and fractured structure which the rocks of the land so universally present. If the solid crust of the earth is allowed to be about 25 miles thick, we must conceive that in the lower four-fifths of its mass the rocks are in a condition of latent plasticity. They lie much beyond the crushing strength which they exhibit at the surface. They are not crushed into powder as they would be under a similar strain above ground, but they are ready to yield to the deformations that may arise consequent upon readjustments of the gigantic pressure to which they are subjected. Hence the solid crust down as far as its structure has been disclosed abounds in proofs that it has undergone colossal plication and fracture, and that higher portions of it many square miles in extent have been thrust bodily over each other for many miles.

§ 4. **Age of the Earth.**—The age of our planet is a problem which may be attacked either from the geological or the physical side.

1. The geological argument rests chiefly upon the observed rates at which geological changes are being effected at the present time, and proceeds on data partly of a physical and partly of an organic kind. (*a*) The physical evidence is derived from such facts as the observed rates at which the surface of a country is lowered by rain and streams, and new sedimentary deposits are formed. These facts, to be adequately appreciated, must be stated in detail, as will be done in later sections of this volume. It may suffice here to refer to the slowness with which such changes are now taking place before our eyes, and to state that if we assume that the land has been worn away, and that stratified deposits have been laid down, nearly at the same rate as at present, then we must admit that the stratified portion of the crust of the earth must represent a very vast period of time. (*b*) The evidence from the organic world is not less cogent in support of the demand for long periods of time. Human experience, so far as it goes, warrants the belief that changes in the structure of plants and animals take place with extreme slowness. Yet in the stratified rocks of the terrestrial crust we have abundant proof that the whole fauna and flora of the earth's surface have passed through numerous cycles of revolution—species, genera, families, orders, appearing and disappearing many times in succession. On any allowable supposition, these vicissitudes in the

[1] *Op. cit.* p. 410.

organic world can only have been effected with the lapse of vast periods of time, though no reliable standard seems to be available whereby these periods are to be measured.

It will be observed that this geological reasoning is based on the assumption that on the whole the changes in the inorganic and organic worlds have advanced in the past at much the same rate as they do at present. It is not maintained that this rate has never varied, but it is the only one with which we are acquainted, and which can therefore be taken as a guide in the investigation and interpretation of the past history of the earth. But the reasoning has been impugned on the ground that the present scale of geological and biological processes may be far slower than it once was, and cannot therefore be taken as a reliable basis.[1] Some of those who have entered into this discussion from the side of physics, starting from the postulate, which no one will dispute, that the total sum of terrestrial energy was once greater than now, and has been steadily declining, have boldly asserted that all kinds of geological action must have been more vigorous and rapid during bygone ages than they are to-day; that volcanoes were more gigantic, earthquakes more frequent and destructive, mountain-upthrows more stupendous, tides and waves more powerful, and commotions of the atmosphere more violent, together with more disastrous tempests, heavier rainfall, and more rapid denudation. But no proofs have ever been brought forward to show that these assertions are founded on actual fact and not on mere theoretical possibility. Such proofs, if they existed, could be produced, for they would assuredly be found in the chronicle of the earth's history, which from a very early period down to the present time has been legibly written within the sedimentary formations of the terrestrial crust. But that chronicle has been scrutinised in all quarters of the globe without the discovery of any evidence in favour of the assertions of the physicists. No indication has been found that the rate of geological causation has ever, on the whole, greatly varied during the time which has elapsed since the deposition of the oldest stratified rocks. While it is not contended that there has been no variation, that there have been no periods of greater activity, both hypogene and epigene, the demonstration of the existence of such periods has yet to be made. It may be most confidently affirmed that, whatever may have happened in the early ages of which there is no available geological record, in the whole vast succession of sedimentary strata nothing has yet been detected which necessarily demands that more violent and rapid action which, from physical reasoning, has been supposed to have been the order of nature during the past.

The validity of this statement will appear more clearly from the detailed account of the structure of the terrestrial crust to be given in later parts of this volume. But it may be of service here to direct attention

[1] Some of the passages which follow are taken from my Address to the Geological Section of the British Association at the Dover Meeting in 1899. In that Address, and in the Presidential Address to the British Association at Edinburgh in 1892, I have dealt with the question of the probable age of the earth.

to some of the kinds of geological evidence which may be appealed to in its favour. In so far as relates to the effects of underground energy, it may be confidently asserted that the latest mountain-upheavals were at least as stupendous as any of older date whereof the basal relics can yet be detected. They seem, indeed, to have been still more gigantic than those. It may be doubted, for example, whether among the vestiges that remain of Mesozoic or Palæozoic mountain-chains, any instance can be found of uplifts so colossal as those of Tertiary times, such as that of the Alps. No known volcanic eruptions of the older geological periods can compare in extent or volume with those of Tertiary and recent date. The plication and dislocation of the terrestrial crust are proportionately as conspicuously displayed among the younger as among the older formations, though the latter, from their greater antiquity, have suffered more frequently and during a longer time.

Then with regard to the geological changes on the surface of the earth, no evidence of greater violence in the surrounding envelopes of atmosphere and ocean has been yet found among the stratified rocks. One of the very oldest formations of Western Europe, the Torridon Sandstone of North-West Scotland, presents us with a picture of long-continued sedimentation, such as may be seen in progress now round the shores of many a mountain-girdled lake. In that venerable deposit, the enclosed pebbles are not mere angular blocks and chips, swept by a sudden flood or destructive tide from off the surface of the land, and huddled together in confused heaps over the floor of the sea. They have been rounded and polished by the quiet operation of running water, as stones are rounded and polished now in the channels of brooks or on the shores of lake and sea. They have been laid gently down above each other, layer over layer, with fine sand sifted in between them. So tranquil were the waters in which these sediments accumulated, that their gentle currents and oscillations sufficed to ripple the sandy floor, to arrange the sediment in laminæ of current-bedding, and to separate the grains of sand according to their relative densities. We may even now trace the results of these operations in thin darker layers and streaks of magnetic iron, zircon, and other heavy minerals, which have been sorted out from the lighter quartz-grains, as layers of iron-sand may be seen sifted together by the tide along the upper margins of many of our sandy beaches at the present day. In the same ancient formation there occur also various intercalations of fine muddy sediment, so regular in their thin alternations, and so like those of younger formations, that they may eventually yield remains of organisms which, if found, would be the earliest traces of life in Europe.

It is thus abundantly manifest that even in the most ancient of the sedimentary registers of the earth's history, not only is there no evidence of colossal floods, tides, and denudation, but there is incontrovertible proof of continuous orderly deposition, such as may be witnessed to-day in any quarter of the globe. The same tale, with endless additional details, is told all through the stratified formations down to those which are in the course of accumulation at the present day.

Not less important than the stratigraphical is the palæontological evidence in favour of the general quietude of the epigene geological processes in the past. The conclusions drawn from the nature and arrangement of the sediments are corroborated and much extended by the structure and manner of entombment of the enclosed organic remains. From the time of the very earliest fossiliferous formations there is nothing to show that either plants or animals have had to contend with physical conditions of environment different, on the whole, from those in which their successors now live. The oldest trees, so far as regards their outer form and internal structure, betoken an atmosphere neither more tempestuous nor obviously more impure than that of to-day, though there may have been formerly a greater proportion of carbon-dioxide in the air. The earliest corals, sponges, crustaceans, mollusks, and arachnids were not more stoutly constructed than those of later times, and are found grouped together among the rocks as they lived and died, with no apparent indication that any violent commotion of the elements tried their strength when living, or swept away their remains when dead.

But, undoubtedly, most impressive of all the palæontological data is the testimony borne by the grand succession of organic remains among the stratified rocks as to the vast duration of time required for their evolution. We do not know the present average rates of organic variation, but all the available evidence goes to indicate their extreme slowness. They may conceivably have been more rapid in the past, or they may have been liable to fluctuations according to vicissitudes of environment. But those who assert that the rate of biological evolution ever differed materially from what it may now be inferred to be, have still to bring forward something more than mere assertion in their support. Some biologists conceive that the whole succession of plant and animal life preserved in the crust of the earth might have been evolved in some such period as 20 or 30 millions of years. But the great majority of them, with Darwin at their head, have contended for a much more liberal allowance of time.[1]

Until it can be shown that geologists and palæontologists have misinterpreted the records contained in the earth's crust, they may not unreasonably claim as much time for the history revealed in these records as the vast body of accumulated evidence appears to them to demand. There is a general agreement among the geologists that so far as the phenomena of sedimentation and tectonic structure are concerned 100 millions of years would probably suffice for the completion of the geological record. But if on palæontological grounds the allowance of time should be found too small, there appears to be no reason, on at least the geological side, why it should not be enlarged, as far as may be found

[1] Darwin's 'Origin of Species,' chap. ix.; 'Life and Letters,' iii. pp. 115, 146. Professor Poulton in his Presidential Address to the Zoological Section of the British Association at Liverpool in 1896 has fully stated the biological arguments and their bearing on the age of the earth. Professor Sollas has expressed the opinion that the demands of biology would be amply satisfied with a period of 26 millions of years (Address to Section C, Brit. Assoc. 1900, p. 12 of reprint).

needful for the satisfactory interpretation of the evolution of organised existence on the globe.

An ingenious and new geological argument has recently been based by Professor J. Joly of Trinity College, Dublin, on the quantity of sodium present in the water of the ocean as a measure of the age of the earth. He assumes that the sodium contained in that water was not derived from the primeval atmosphere or the original constitution of the ocean, but has been supplied in the long course of geological time by the denudation of the land and the consequent removal of the material in solution from the terrestrial rocks. The total volume of the oceanic water may be approximately computed, and as the chemical composition of this water is fairly well known from the analysis of specimens taken from many widely separated regions, the whole amount of sodium in the ocean may likewise be calculated. Again, the total volume of fresh water annually draining off the land into the sea may be estimated, and from the examination of the salts held in solution in the waters of a number of rivers an approximate average may be reached for the quantity of sodium carried in solution every year into the sea. Using therefore the quantity of sodium in the ocean as a numerator and that supplied every year by the drainage of the land as a denominator, Professor Joly arrives at the conclusion that if, as may reasonably be assumed, the present annual supply be taken as a measure of what has been the rate in past time, a period of between 90 and 100 millions of years has elapsed since the ocean began to receive its tribute of chemical solution from the land. It may be objected to this reasoning that some of the sodium was present in the original atmosphere and ocean, and if this were the case the length of time demanded would be proportionately reduced. Professor Joly, however, gives reasons for his belief that the sodium, as well as most of the metals, was silicated in the earliest terrestrial crust, and that the chlorine probably existed as a gas combined with hydrogen in the primeval atmosphere or dissolved as an acid in the earliest water, and he makes an allowance for the more active denudation which such a condition of things would entail. Another objection obviously arises to the uniformitarian basis on which the computations are made. But it has been pointed out above that the present rate of geological change, being the only one which we can actually witness and measure, affords the only foundation on which to proceed in endeavouring to estimate the value of past geological time. It is interesting to perceive that the time-limit deduced by this novel method of investigation accords well with the conclusions which on other grounds geologists had already reached as to the antiquity of the globe.[1]

[1] "An Estimate of the Geological Age of the Earth," by Professor J. Joly, *Trans. Roy. Dublin Soc.* vii. (ser. ii.), 1899, p. 23; *Geol. Mag.* 1900, p. 220; *Rep. Brit. Assoc.* 1900, pp. 369-379. A suggestion had previously been made by Mr. Mellard Reade as to the computation of a limit to the earth's age from the proportion of calcium sulphate in the sea ('Chemical Denudation in relation to Geological Time,' London, 1879). For remarks on Professor Joly's argument, see Rev. O. Fisher, *Geol. Mag.* 1900, p. 124: Professor Sollas, Address to Geological Section of the British Association, 1900. See also a paper by Professor

We may sum up the geological argument for the age of the earth thus:—The geological evidence indicates an interval of probably not much less than 100 million years since the earliest forms of life appeared upon the earth and the oldest stratified rocks began to be laid down.

2. The physical argument as to the age of our planet is based upon three kinds of evidence:—(1) the internal heat and rate of cooling of the earth; (2) the tidal retardation of the earth's rotation; and (3) the origin and age of the sun's heat.

(1) Applying Fourier's theory of thermal conductivity, Lord Kelvin pointed out as far back as the year 1862, that in the known rate of increase of temperature downward beneath the surface, and the rate of loss of heat from the earth, we have a limit to the antiquity of the planet. He showed, from the data available at the time, that the superficial consolidation of the globe could not have occurred less than 20 million years ago, or the underground heat would have been greater than it is; nor more than 400 million years ago, otherwise the underground temperature would have shown no sensible increase downwards. He admitted that very wide limits were necessary. In subsequently discussing the subject, he inclined rather towards the lower than the higher antiquity, but concluded that the limit, from a consideration of all the evidence, must be placed within some such period of past time as 100 millions of years. He would now restrict the time to between 20 and 40 millions.[1]

(2) The reasoning from tidal retardation proceeds on the admitted fact that, owing to the friction of the tidal-wave, the rotation of the earth is retarded, and is therefore slower now than it must have been at one time. Lord Kelvin contends that had the globe become solid some 10,000 million years ago, or indeed any high antiquity beyond 100 million years, the centrifugal force due to the more rapid rotation must

Joly on "The Circulation of Salt and Geological Time," *Geol. Mag.* 1901, p. 344, and subsequent correspondence, pp. 445, 504, 558. Professor E. Dubois has discussed the amount of carbonate of lime in circulation on the earth, and has arrived at the conclusion that "the formation of the carbonates from silicate rocks has required at least some tens of millions of years. But this is a minimum; the real lapse of time since the formation of a solid crust and the appearance of life upon the globe may be more than 1000 millions of years" (*Proc. Kon. Akad. Amsterdam*, 1900, p. 130).

[1] *Trans. Roy. Soc. Edin.* xxiii. p. 157. *Trans. Geol. Soc. Glasgow*, iii. p. 25. 'Popular Lectures and Addresses,' 2nd edit. (1891), p. 397. Professor Tait reduced the period to 10 or 15 millions. 'Recent Advances in Physical Science,' p. 167. From the results of a series of experiments by Dr. Carl Barus to determine the latent heat of fusion, specific heats melted and solid, and volume-expansion between the solid and melted state of the rock diabase, the late Mr. Clarence King arrived at the conclusion that "we have no warrant for extending the earth's age beyond 24 millions of years" (*Amer. Journ. Sci.* xlv. 1893, p. 15). Referring to Mr. King's paper, Lord Kelvin states that he is not led to differ much from the age-limit given in that paper (*Phil. Mag.* January 1899). On the other hand, Professor Perry regards Mr. King's reasoning as inconclusive, and remarks that "it is evident, if we take any probable law of temperature of convective equilibrium at the beginning, and assume that there may be greater conductivity inside than on the surface rocks, Mr. King's ingenious test for liquidity will not bar us from almost any great age" (*Nature*, li. 1895, p. 583).

have given the planet a very much greater polar flattening than it actually possesses. He admits, however, that though 100 million years ago that force must have been about 3 per cent greater than now, yet "nothing we know regarding the figure of the earth and the disposition of land and water would justify us in saying that a body consolidated when there was more centrifugal force by 3 per cent than now, might not now be in all respects like the earth, so far as we know it at present."[1]

(3) The third kind of evidence leads to results similar to those derived from the two previous lines of reasoning. It is based upon calculations as to the amount of heat that would be available by the falling together of masses from space, which by their impact gave rise to our sun, and the rate at which this heat has been radiated. Assuming that the sun has been cooling at a uniform rate, Professor Tait concluded that it cannot have supplied the earth, even at the present rate, for more than about 15 or 20 million years.[2] Lord Kelvin also believes that the sun's light will not last more than 5 or 6 millions of years longer.[3]

These three great physical arguments have for some forty years been repeatedly advanced as a triumphant demolition of the uniformitarian doctrines of modern days. They are alleged "to sweep away the whole system of geological and biological speculation demanding an 'inconceivably' great vista of past time, or even a few thousand million years, for the history of life on the earth, and approximate uniformity of plutonic action throughout that time." Yet when examined they are each found to rest on assumptions which, though certified as "probable" or "very sure," are nevertheless admittedly assumptions. The conclusions to which these assumptions lead must depend for their validity on the degree of approximation to the truth in the premisses which are postulated. As Huxley in dealing with them long ago remarked in his characteristically forcible way, "Mathematics may be compared to a mill of exquisite workmanship, which grinds you stuff of any degree of fineness; but, nevertheless, what you get out depends on what you put in; and as the grandest mill in the world will not extract wheat-flour from peascods, so pages of formulæ will not get a definite result out of loose data."[4]

It is important to observe that neither the assumptions nor the conclusions drawn from them are so self-evident as to have commanded universal assent even among physicists themselves. In the year 1886 Professor George Darwin devoted his Presidential Address before the Mathematical Section of the British Association to a review of the three famous physical

[1] *Trans. Geol. Soc. Glasgow*, iii. p. 16. Professor Tait, in repeating this argument, concluded that, taken in connection with the previous one, "it probably reduces the possible period which can be allowed to geologists to something less than 10 millions of years." 'Recent Advances,' p. 174. Compare Newcomb, 'Popular Astronomy,' p. 505.

[2] *Op. cit.* p. 174.

[3] 'Popular Lectures,' etc., p. 397. His latest pronouncement on this subject will be found in his "Address to the Victoria Institute," *Phil. Mag.* January 1899, in which, departing from his original more liberal estimate, he now affirms that the age of the earth "was more than 20 and less than 40 million years, and probably much nearer 20 than 40."

[4] Presidential Address to Geological Society, 1869.

arguments respecting the age of the earth. He summed up his judgment of them in the following words: "In considering these three arguments I have adduced some reasons against the validity of the first [tidal friction], and have endeavoured to show that there are elements of uncertainty surrounding the second [secular cooling of the earth]; nevertheless they undoubtedly constitute a contribution of the first importance to physical geology. Whilst, then, we may protest against the precision with which Professor Tait seeks to deduce results from them, we are fully justified in following Sir William Thomson, who says that 'the existing state of things on the earth, life on the earth—all geological history showing continuity of life—must be limited within some such period of past time as 100 million years.'"[1]

Three years later Mr. R. S. Woodward, from the mathematical side, expressed his opinion that the argument drawn from the cooling of the earth was probably incorrect, and that this contention of the physicists remained as doubtful as it was when discussed twenty years before by Huxley.[2] Again, at the beginning of the year 1900 the same able mathematician reaffirmed the conviction he had previously published, remarking that Lord Kelvin had not convinced most mathematicians, and the geologists had adduced the weightier arguments. He added these words: "Beautiful as the Fourier analysis [of the theory of heat conduction] is, and absorbingly interesting as its application to the problem of a cooling sphere is, it does not seem to me to afford anything like so definite a measure of the age of the earth as the visible processes and effects of stratification to which the geologists appeal."[3]

More recently each of the three physical arguments has been impugned on physical grounds by Professor Perry. In regard to the first of them, based on the rate of cooling of the earth, he contends that it is perfectly allowable to assume a much higher conductivity for the interior of the globe, and this assumption will vastly increase our estimate of the age of the planet. The second, based on tidal retardation, which had already been impugned by Mr. Maxwell Close and Professor Darwin, is dismissed by him as fallacious. With respect to the third, drawn from the history of the sun, he maintains that, on the one hand, the sun may have been repeatedly fed by infalling meteorites, and that on the other the earth, during former ages, may have had its heat retained by a dense atmospheric envelope. Believing that "almost anything is possible as to the present internal state of the earth," he concludes in these words: "To sum up, we can find no published record of any lower maximum age of life on the earth, as calculated by physicists, than 400 millions of years. From the three physical arguments, Lord Kelvin's higher limits are 1000, 400, and 500 million years. I have shown that we have reasons for believing that the age, from all these, may be very considerably underestimated. It is

[1] *Rep. Brit. Assoc.* 1886, p. 517.

[2] "On the Mathematical Theories of the Earth," Vice-Presidential Address to the Section of Astronomy and Mathematics, Amer. Assoc. 1889.

[3] "The Century's Progress in Mathematics," Presidential Address, *Bull. American Math. Soc.* vi. (1900), p. 147.

to be observed that if we exclude everything but the arguments from mere physics, the *probable* age of life on the earth is much less than any of the above estimates; but if the palæontologists have good reasons for demanding much greater time, I see nothing from the physicist's point of view which denies them four times the greatest of these estimates."[1]

This remarkable admission from a recognised authority on the physical side re-echoes and emphasises the warning pronounced by Professor Darwin in the address already quoted: "At present our knowledge of a definite limit to geological time has so little precision that we should do wrong to summarily reject any theories which appear to demand longer periods than those which now appear allowable."[2] It is fully recognised that the exorbitant demands for past time made by the earlier geologists were unwarranted and unnecessary, and that physicists have done notable service in showing that a limit must be set to the antiquity of the globe and to the future duration of the solar system. But the physical arguments are not based on such definite and precisely known data as to prevent the geologists and palæontologists of to-day from claiming as much time as the obvious interpretation of the structure and history of the earth's crust appears to demand.

The sequence of geological time and the methods of arranging its subdivisions and of attempting to compute their relative duration will be better understood by the student after the composition and tectonic arrangements of the terrestrial crust have been considered in Book VI.

## PART II.—AN ACCOUNT OF THE COMPOSITION OF THE EARTH'S CRUST—MINERALS AND ROCKS.

The earth's crust is composed of mineral matter in various aggregates included under the general term Rock. A rock may be defined as a mass of matter composed of one or more simple minerals, having usually a variable chemical composition, with no necessarily symmetrical external form, and ranging in cohesion from mere loose débris up to the most compact stone. Granite, lava, sandstone, limestone, gravel, sand, mud, soil, marl and peat, are all recognised in a geological sense as rocks. The study of rocks is known as Lithology, Petrography or Petrology.

It will be most convenient to treat—1st, of the general chemical constitution of the crust; 2nd, of the minerals of which rocks mainly consist; 3rd, of the methods employed for the determination of rocks; 4th, of the external characters of rocks; 5th, of the internal texture and structure of rocks; 6th, of the classification of rocks; and 7th, of the more important rocks occurring as constituents of the earth's crust.

### Sect. i. General Chemical Constitution of the Crust.

Direct acquaintance with the chemical constitution of the globe must obviously be limited to that of the crust, though by inference we may

[1] *Nature*, li. (1895), p. 585. [2] *Rep. Brit. Assoc.* 1886, p. 518.

eventually reach highly probable conclusions regarding the constitution of the interior. Chemical research has discovered that some seventy-five simple or as yet undecomposable bodies, called elements, in various proportions and compounds, constitute the accessible part of the crust. Of these, however, the great majority are comparatively of rare occurrence. The crust, so far as we can examine it, is mainly built up of about twenty elements, which may be arranged in two groups,—metalloids and metals,—the most abundant bodies being placed first in each group in the following table:[1]—

| | Chemical Symbol. | Atomic Weight. | A. Proportion in the Older Crust of the Earth. | B. Proportion in outer part of Earth, including Crust, Sea, and Atmosphere. |
|---|---|---|---|---|
| *Metalloids.* | | | | |
| Oxygen | O | 15·96 | 47·02 | 50 |
| Silicon | Si | 28·00 | 28·06 | 26 |
| Hydrogen | H | 1·00 | 0·17 | 0·90 |
| Carbon | C | 11·97 | 0·12 | 0·20 |
| Phosphorus | P | 30·96 | 0·09 | 0·08 |
| Sulphur | S | 31·98 | 0·07 | 0·06 |
| Chlorine | Cl | 35·37 | 0·01 | 0·175 |
| Fluorine | F | 19·00 | 0·01 | 0·03 |
| Nitrogen | N | 14·01 | ... | 0·02 |
| *Metals.* | | | | |
| Aluminium | Al | 27·30 | 8·16 | 7·45 |
| Iron | Fe | 55·90 | 4·64 | 4·2 |
| Calcium | Ca | 39·90 | 3·50 | 3·25 |
| Magnesium | Mg | 23·94 | 2·62 | 2·35 |
| Potassium | K | 39·04 | 2·35 | 2·35 |
| Sodium | Na | 22·99 | 2·63 | 2·40 |
| Titanium | Ti | 48·00 | 0·41 | 0·30 |
| Manganese | Mn | 54·80 | 0·07 | 0·07 |
| Barium | Ba | 136·80 | 0·05 | 0·03 |
| Strontium | St | 87·20 | 0·02 | 0·005 |
| Chromium | Cr | 52·40 | 0·01 | 0·01 |
| Nickel | Ni | 58·60 | 0·01 | 0·005 |
| Lithium | Li | 7·01 | 0·01 | 0·005 |
| | | | 100·00 | |

Of the other elements, upwards of fifty in number, the proportions are so small that probably not one of them equals as much as one-hundredth of one per cent of the whole crust. Yet they include gold, silver, copper, tin, lead and the other useful metals, iron excepted. It will be observed that of the accessible part of the globe three-fourths consist of metalloids and one-fourth of metals.

[1] Column A is taken from the paper by Mr. F. W. Clarke, *Bull. U.S. Geol. Surv.* No. 168 (1900), p. 5. The proportions of the elements here given were estimated from the complete analyses of 830 rocks representing the general composition of the older crystalline rocks of the terrestrial crust. This subject has likewise been elaborately worked out for each element or group of elements by Professor Vogt of Christiania (*Zeitsch. Prakt. Geol.* 1898, pp. 225, 314, 377, 413; and 1899, p. 10). Column B in the table above, taken from his papers, shows the proportion of the elements assigned by him to the rocks, the air, and the sea,

Comparatively few of the elements occur in a free or uncombined state. In nearly all cases they have formed compounds with each other, some of which consist of only two elements, while others have an exceedingly complicated composition. We may conveniently consider the more important elements in the order of their relative abundance and notice the chief combinations in which they occur.

**Oxygen**, by far the most abundant constituent of the outer part of our planet, forms about 23 per cent by weight of air, 88·87 per cent of water, and about half of all the rocks that compose the terrestrial crust. It exists free or mechanically mixed with nitrogen in the atmosphere, from which it readily passes into combination with the other elements (with all of which it forms compounds, except with fluorine) in the large and widely prevalent series of Oxides. These may be divided into Basic Oxides, which combine with acids to form salts, as where iron-monoxide or ferrous oxide, $FeO$, combines with carbonic dioxide to form ferrous carbonate or spathic iron; Peroxides, which contain a larger proportion of oxygen and do not form salts; familiar examples being the sesquioxide of iron or ferric oxide ($Fe_2O_3$) and manganese dioxide ($MnO_2$); and Acid-forming Oxides, which, combining with water, form acids, as where the trioxide of sulphur ($SO_3$) taking up water becomes sulphuric acid ($H_2SO_4$), and the pentoxide of phosphorus ($P_2O_5$) becomes phosphoric acid ($H_3PO_4$).

**Silicon**, which ranks second in importance, always occurs united with oxygen. It constitutes rather more than a fourth part of the crust. Its dioxide, known as Silica, is found as the familiar mineral quartz, and as one of the acid-forming oxides ($H_4SiO_4$, Silicic acid)[1] it forms combinations with alkaline, earthy, and metallic bases, which appear as the prolific and universally diffused family of the Silicates. Moreover, it is present in solution in terrestrial and oceanic waters, from which it is deposited in pores and fissures of rocks. It is likewise secreted from these waters by abundantly diffused species of plants and animals (diatoms, radiolarians, &c.). It has been largely effective in replacing the organic textures of former organisms, and thus preserving them as fossils. Silica may be regarded as the most abundant and important ingredient in the mineral kingdom, for of itself it makes up more than one-half of the known crust, which it seems to bind firmly together, entering as a main ingredient into the composition of most crystalline and fragmental rocks as well as into the veins that traverse them. Quartz strongly resists ordinary decay, and is therefore a marked constituent of many of the more enduring kinds of rock. Many of the silicates, however, are liable to decay, owing to their decomposition and the abstraction of their bases.

**Aluminium** comes third in order of the elements as a constituent of the crust, of which it is computed to form about 8 per cent. It is thus by far the most abundant of all the metals. It is not found naturally in the free state, but combined with oxygen forms several distinct minerals (corundum, sapphire, ruby), and occurs also in the material known as bauxite (p. 169), now much sought after as a source for the extraction of the metal. Its chief combinations, however, are with silica, with which it forms the basis of the vast family of the aluminous silicates that constitute so large a portion of the crystalline and fragmental rocks. Exposed to the atmosphere, these silicates lose some of their more soluble ingredients, and the remainder forms an earth or clay consisting chiefly of silicate of aluminium.

**Iron**, the fourth element in order of abundance in the terrestrial crust, of which it forms nearly 5 per cent, occurs in the free state alloyed with nickel as the main constituent of the class of meteorites known as siderites, and has also been detected in some

[1] This is the normal quadrivalent or orthosilicic acid in which one atom of silicon is united to four of $H_2O$; but there are probably other silicic acids in nature giving rise to diortho-silicates, meta-silicates and dimeta-silicates. F. W. Clarke, *B. U. S. G. S.* No. 125 (1895). See also G. F. Becker, *Amer. Journ. Sci.* xxxviii. (1889), p. 154.

terrestrial rocks of volcanic origin, as will be more fully noticed a little farther on. But with these exceptional occurrences, it is always combined with oxygen, with which it forms a varied and universally diffused group of oxides. The monoxide or ferrous oxide (FeO) is an abundant constituent of rocks. The sesquioxide or ferric oxide ($Fe_2O_3$), though rather less prevalent, is a common mineral, and is likewise present in the composition of many igneous and sedimentary rocks. Reference to these minerals is made on p. 96. The monoxide is abundantly diffused in combination with carbonic acid as the carbonate of iron—an important ore of the metal. United to sulphur, iron yields an important group of sulphides. Iron and manganese are frequently associated together in igneous rocks, and likewise in the sedimentary strata derived from these.[1]

**Calcium**, a metal, forming with Barium and Strontium the group of the alkaline earths, comes rather behind iron in abundance, and never occurs in a free state. Combined with oxygen and united with one or other of the acids, it gives rise to an abundant and varied series of compounds, and hence becomes an important rock-constituent both among the igneous and sedimentary formations. Thus in combination with silica it enters into the composition of many silicates, and in union with carbon-dioxide it appears as the mineral calcite, so widely spread in strings and cavities of rocks exposed to the action of meteoric waters, and as the various kinds of limestone. Calcium-carbonate or carbonate of lime being soluble in water containing carbonic acid, is one of the most universally diffused mineral ingredients of natural waters. It supplies the varied tribes of mollusks, corals, and many other invertebrates with mineral substance for the secretion of their tests and skeletons. Such too has been its office from remote geological periods, as is shown by the vast masses of organically-formed limestone, which enter so conspicuously into the structure of the continents. In combination with sulphuric acid, calcium forms important beds of gypsum and anhydrite.

**Magnesium**, another metal, is not met with uncombined, but its oxide occurs not infrequently in combination with carbonic acid, sulphuric acid and silicic acid; while, united to chlorine, magnesium is found abundantly in the sea and in some ancient rock-salt deposits.

**Sodium** and **Potassium**, the two chief alkali metals, are only met with in combination with other elements. United to silicic acid they are widely diffused among the silicates, and combined with chlorine they appear as important members of the saline constituents of the sea, as well as in the deposits of rock-salt within the earth's crust.

The foregoing eight elements form together about 99 per cent of the crust. It will be seen that even the most abundant of the remaining elements enumerated in the table exists in such small quantity as not to amount to as much as the half of one per cent, while the others are found in still more minute proportions. The most important of them appears to be Titanium.

**Titanium** does not occur native. As an oxide it forms the minerals anatase, brookite and rutile. But its prevalent association is with iron as titanic iron, $(FeTi)_2O_3$, in which form it is present in many igneous rocks (basalts and other basic masses), and even in the ferrous carbonates which occur among the stratified formations and are employed as ores of iron, for it is found in brilliant aggregates in the bottom-slags of smelting furnaces.

**Hydrogen** has been found in a free state at volcanic vents, and has been detected in notable quantities enclosed in the minute pores or cavities of many igneous rocks of all ages. Thus in a gabbro from the Lizard, Cornwall, it has been obtained to the amount of six times the volume of the enclosing rocks.[2] It has been found occluded in meteorites. It chiefly occurs, however, in combination with oxygen as the oxide, water, of which it forms 11·13 per cent by weight; also in combination with carbon as the hydrocarbons (mineral oils and gases).

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[1] R. A. F. Penrose, jun., "The Chemical Relation of Iron and Manganese in Sedimentary Rocks," *Journ. Geol.* i. (1893), p. 356.

[2] Dr. W. A. Tilden, *Proc. Roy. Soc.* lx. (1897), p. 453.

**Carbon** is the fundamental element of organic life. In combination with oxygen it forms two oxides—carbon monoxide (CO), a gas which has been found in some quantity in the minute pores of igneous rocks; and carbon dioxide ($CO_2$), which is a universal and powerful geological agent. Combined with hydrogen it yields methane, marsh-gas or fire-damp ($CH_4$), which has been likewise found to be present in the microscopic cavities of igneous rocks. Compounds of carbon with hydrogen, as well as with oxygen, nitrogen and sulphur, form the various kinds of coal. Carbon-dioxide is present in the air, in rain, in the sea and in ordinary terrestrial waters. This oxide, being soluble in water,[1] gives rise to a dibasic acid termed Carbonic Acid, $CO(OH)_2$ or $H_2CO_3$, which forms carbonates, its combination with calcium having been instrumental in the formation of vast masses of solid rock. Carbon-dioxide constitutes a fifth part of the weight of ordinary limestone.

From the detection of marsh-gas and carbonic acid in considerable quantities imprisoned within the minute pores of igneous rocks, and from the abundant escape of hydrocarbons in the gaseous and liquid form from beneath to the surface in so many parts of the world, the opinion has been formed that these emanations do not proceed, as has generally been supposed, from the decomposition of coal or other sedimentary material of carbonaceous composition and vegetable origin, but rather point to the existence of vast quantities of carbon combined in the interior of the earth with such metals as iron and manganese. Water descending from the surface and reaching these carbides, which are readily decomposable by water, one class of them even at ordinary temperatures and pressures, would give rise to the oxidation of the metals, to the production of hydrocarbons, both gaseous and liquid, and to the evolution of carbonic acid as the ultimate stage of alteration.[2]

**Phosphorus** is not met with in the free state, but is widely diffused in nature combined with oxygen and calcium as calcium phosphate, which in small quantities appears in many crystalline rocks (apatite). By the decay of these rocks it is furnished to the soil, and becomes an important ingredient in plant-structures, and enters largely into the composition of mammalian bones. It is found in layers and nodules in many sedimentary rocks (phosphatic chalk, coprolites, &c.).

**Manganese** is another of the widely diffused metals which are never found in the native state. In combination with oxygen it yields a series of oxides, some of which occur as independent minerals. It is present in minute quantities in other minerals, and can be detected in many rocks. Reference is made on p. 97 to some of these occurrences.

**Sulphur** occurs uncombined at some volcanic vents and in occasional sedimentary deposits, like those of Sicily and Naples, to be afterwards described; but much more commonly in union with iron and other metals as sulphides; and in combination with oxygen as sulphuric acid, $H_2SO_4$, in sulphates of lime, magnesia, &c. In the form of gypsum, calcium sulphate becomes an important rock-builder among certain groups of deposits.

**Barium**, never met with uncombined, is chiefly found in the form of a sulphate, known as barytes or heavy spar, of frequent occurrence in mineral veins and filling cavities in rocks into which it has been introduced by infiltration. The carbonate, witherite, is not so abundant, and the element occurs in still smaller quantities in a number of minerals, in some mineral waters, and in the sea.

**Strontium**, like barium, does not occur in the free state, but is not very rare combined with sulphuric acid as the sulphate called celestine, and with carbon-dioxide as the carbonate or strontianite. Minute admixtures of strontium are likewise present in some other minerals (calcite, aragonite, and limestone), and in the water of some springs and of the sea.

[1] One volume of water at 0° C. dissolves 1·7967 volumes of carbon-dioxide; at 15° C. the amount is reduced to 1·0020 volumes.

[2] Mendelejeff's 'Principles of Chemistry,' i. p. 364; H. Moissan, *Proc. Roy. Soc.* lx. (1897), p. 156; Tilden's paper above cited, and W. Ramsay, *Proc. Roy. Soc.* xl. (1897). This subject is again referred to at p. 142, and will be further discussed in Book III. Part I. Sect. i. § 5.

**Nickel** is a metal which appears in variable proportions alloyed with native iron in meteorites, and also in the native iron found in some terrestrial volcanic rocks. It occurs in combination with other elements in various minerals and ores, such as nickeline or kupfer-nickel, nickel-glance, millerite, nickel-ochre, garnierite, &c.

**Chromium** is one of a distinct group of metals which furnish acid-forming trioxides that yield well-marked salts. It is not met with in the free state, but occurs as a constituent of various minerals, particularly in chromite or chromic iron, and as the green colouring material of others, as in the emerald, and some micas and serpentines.

**Lithium**, another of the alkali metals, is the lightest of all known solid substances, but it does not occur native. It is found in combination with phosphates and silicates in several minerals, and minute proportions of it are present in many natural waters.

**Chlorine** does not occur in nature in a free state, but appears abundantly in combination with the alkali metals, in the form of the chlorides of sodium, potassium and magnesium, which are such characteristic constituents of sea-water. These compounds are likewise met with in ancient rock-salt deposits. On a comparatively trifling scale this element also occurs in combination with metals in different minerals, as with iron, lead, silver and copper.

**Fluorine** is an element so much more active than all the others that it combines with every one of them, save only oxygen. Until recently it had resisted all the attempts of chemists to isolate it, but this separation has at last been effected by M. Moissan of Paris, who has found it to be a pale yellowish-green gas which becomes liquid at a temperature of about $-187°$ C.[1] Its most familiar combination in nature is with calcium (fluor-spar), but it occurs also with aluminium and sodium (cryolite) and in other minerals. Traces of its presence have been detected in the water of many mineral springs and of the sea, and likewise in the structure, especially the bones and teeth, of mammals. The remarkable researches of M. Moissan have demonstrated such an extraordinary chemical activity of this element with regard to the metalloids, metals and even organic compounds, that the presence of fluorine, even if only in minute proportions, may be looked for in any terrestrial substance.

Of the elements here enumerated the combinations which enter most largely into the composition of the earth's crust can best be determined from the collation of a sufficiently large number of chemical analyses of the more representative rocks of the earth's crust. Such a determination has been made by Mr. F. W. Clarke from the mean of 830 analyses of typical samples from the older or primitive part of the crust, and is expressed in the subjoined table.[2]

| | |
|---|---|
| Silica ($SiO_2$) | 59·71 |
| Alumina ($Al_2O_3$) | 15·41 |
| Ferric oxide ($Fe_2O_3$) | 2·63 |
| Ferrous oxide ($FeO$) | 3·52 |
| Lime ($CaO$) | 4·90 |
| Magnesia ($MgO$) | 4·36 |
| Potash ($K_2O$) | 2·80 |
| Soda ($Na_2O$) | 3·55 |
| Water ($H_2O$) | 1·52 |
| Titanic acid ($T_1O_2$) | 0·60 |
| Phosphoric acid ($P_2O_5$) | 0·22 |
| | 99·22 |

[1] 'Fluor et ses Composées,' Paris, 1900, pp. xii. 397.

[2] *Bull. U. S. G. S.*, No. 168 (1900), p. 14. According to this enumeration all the other combinations of the elements form considerably less than one per cent.

In a broad view of the arrangement of the chemical elements in the external crust, the speculation of Durocher may be noticed here.[1] He regarded all rocks as referable to two layers or magmas co-existing in the earth's crust, the one beneath the other, according to their specific gravities. The upper or outer shell, which he termed the acid or siliceous magma, contains an excess of silica, and has a mean density of 2·65. The lower or inner shell, which he called the basic magma, has from six to eight times more of the earthy bases and iron-oxides, with a mean density of 2·96. To the former he assigned the early plutonic rocks, granite, felsite, &c., with the more recent trachytes; to the latter he relegated all the heavy lavas, basalts, diorites, &c. The ratio of silica is 7 in the acid magma to 5 in the basic. The proportion of silicic acid or of the earthy and metallic bases cannot, however, be regarded as any certain evidence of the geological date of eruptive rocks, nor of their probable depth of origin.[2]

### Sect. ii. Rock-forming Minerals.[3]

Chemical analysis has revealed the numerous combinations in which the elements are united to form minerals and rocks. Considerable additional light has likewise been thrown on the subject by chemical synthesis, that is, by artificially producing the minerals and rocks which are found in nature. The experiments have been varied indefinitely so as to imitate as far as possible the natural conditions of production. Further reference to this subject will be found on pp. 398-430.

Although every mineral may be made to yield data of more or less geological significance, only those minerals need be referred to here which enter as chief ingredients into the composition of rock-masses, or which are of frequent occurrence as accessories, and special note may be taken of those of their characters which are of main interest from a geological

1 *Ann. des Mines*, 1857. Translated by Haughton, 'Manual of Geology,' 1866, p. 16.

2 In Book III. Part I. Sect. i. § 4, the sequence of volcanic rocks is discussed.

3 There is now an extensive literature of petrography, and numerous text-books in different languages have been published. Some of these deal with rocks as a whole; others treat more specially of their chemical or mineralogical or microscopic characters. Of general works of reference which deal with all sides of the subject, by far the most important is the 'Lehrbuch der Petrographie,' by Professor Zirkel of Leipzig, the second edition of which has appeared in three massive volumes. The following list comprises some of the more historically interesting or generally useful treatises:—Pinkerton, 'Petrology,' London, 1811. J. Macculloch, 'A Geological Classification of Rocks, &c.,' London, 1821. K. von Leonard, 'Characteristik der Felsarten,' 1823. B. von Cotta, 'Rocks Classified and Described,' translated by Lawrence, London, 1866. Senft, 'Classification der Felsarten,' Breslau, 1857; 'Die Krystallinischen Felsgemengtheile,' Berlin, 1868. Kenngott, 'Elemente der Petrographie,' Leipz. 1868. A. von Lasaulx, 'Elemente der Petrographie,' Bonn, 1875. F. Rutley, 'The Study of Rocks,' London, 1879. E. Jannettez, 'Les Roches,' Paris, 1884. E. Hussak, 'Anleitung der Gesteinbildenden Mineralien,' Leipzig, 1885. A. Harker, 'Petrology for Students,' 2nd edit., Cambridge, 1897. D. Gonzalo Moragas, 'Genesis de las Rocas,' Madrid, 1898. Works treating more particularly of the chemical side of petrography are cited on pp. 116-119; those dealing in detail with the microscopic character of rocks at pp. 119, 140-157; those devoted to nomenclature and classification at pp. 157, 195-203.

point of view, such as their modes of occurrence in relation to the genesis of rocks, and their weathering as indicative of the nature of rock-decomposition.

Minerals, as constituents of rocks, occur in four conditions, according to the circumstances under which they have been produced.

(1.) *Crystalline*, as (*a*) more or less regularly defined crystals, which, exhibiting the outlines proper to the mineral to which they belong, are said to be *idiomorphic* or *automorphic;* (*b*) amorphous granules, aggregations or crystalloids, having an internal crystalline structure, in most cases easily recognisable with polarised light, as in the quartz of granite, and an external form which has been determined by contact with the adjacent mineral particles; such crystalline bodies which do not exhibit their proper crystalline outlines are said to be *allotriomorphic* or *xenomorphic;* (*c*) "crystallites" or "microlites," incipient forms of crystallisation, which are described on p. 148. The crystalline condition may arise from igneous fusion, aqueous solution, or sublimation.[1]

(2.) *Glassy* or *vitreous*, as a natural glass, usually including either crystals or crystallites, or both. Minerals have assumed this condition from a state of fusion, also from solution. The glass may consist of several minerals fused into one homogeneous substance. Where it has assumed a lithoid or stony structure, these component minerals crystallise out of the glassy magma, and may be recognised in various stages of growth (*postea*, pp. 141-157).

(3.) *Colloid*, as a jelly-like though stony substance, deposited from aqueous solution. The most abundant mineral in nature which takes the colloid form is silica. Opal is a hardened colloidal condition of this substance. Chalcedony, doubtless originally colloidal silica, now unites the characters of quartz and opal, being only partially soluble in caustic potash and partially converted into a finely fibrous, doubly-refracting substance.

(4.) *Amorphous*, having no crystalline structure or form, and occurring in indefinite masses, granules, streaks, tufts, stainings, or other irregular modes of occurrence.

A mineral which has replaced another and has assumed the external form of the mineral so replaced, is termed a *Pseudomorph*. A mineral which encloses another has been called a *Perimorph;* one enclosed within another, an *Endomorph*.

*Essential or accessory, original or secondary minerals.*—A mineral is an essential ingredient when its absence would so alter the character of a rock as to make it something materially different. The quartz of granite, for example, is an essential constituent of that rock, the removal of which would alter the petrographical species. A mineral is said to be accessory when its absence would not change the essential character of the rock. All essential minerals are original constituents of a rock, but all the original constituents are not essential. In granite, such minerals as topaz, beryl, and sphene often occur under circumstances which show that they crystallised out of the original magma of the rock. But they

[1] For the microscopic characters of minerals and rocks, see p. 140.

form so trifling a proportion in the total mass, and their absence would so little affect the general character of that mass, that they are regarded as accessory, though undoubtedly original and often important ingredients.[1] Again, in rocks of eruptive origin, the essential ingredients cannot be traced back further than the eruption of the mass containing them. They are not only original, as constituents of the lava, but are themselves original and non-derivative minerals, produced directly from the crystallisation of molten minerals ejected from beneath the earth's crust, though, as M. Michel-Lévy has shown, the débris of older minerals may sometimes be traced amidst the later crystals of massive rocks.[2] In rocks of aqueous origin, however, there are many, such as conglomerates and sandstones, where the component minerals, though original ingredients of the rocks, are evidently of derivative origin. The little quartz-granules of a sandstone, for example, have formed part of the rock ever since it was accumulated, and are its essential constituents. Yet each of these once formed part of some older rock, the destruction of which yielded materials for the production of the sandstone. Again, the minute crystals of zircon, rutile, tourmaline, magnetite and other heavy minerals so often found in sands, clays, sandstones, shales and other sedimentary deposits, have been derived from the degradation of older crystalline rocks.

The same mineral may occur both as an original and as a secondary constituent. Quartz, for example, appears everywhere in both conditions; indeed, it may sometimes be found in a twofold form even in the same rock, though there is then usually some difference between the original and secondary quartz. A quartz-felsite, for instance, abounds in original little kernels, or in double pyramids of the mineral, often enclosing fluid cavities, while the secondary or accidental forms usually occur in veins, reticulations, or other irregular aggregates. In some cases, however, as, for example, in sandstones, the secondary quartz has been deposited in optical continuity with that of the original grains, so as to build up new faces and terminations (p. 166).

Accessory minerals frequently occur in cavities where they have had some room to crystallise out from the general mass. The "drusy" cavities, or open spaces lined with well-developed crystals, found in some granites are good examples, for it is there that the non-essential minerals are chiefly to be recognised. The veins of segregation found in many crystalline rocks, particularly in those of the granite series, are further

[1] Some of the "accessory" minerals may be of great importance as indicative of the conditions under which the rock was formed. It is not always possible to discriminate between essential and accessory ingredients in rocks, while some minerals once thought to be secondary have been ascertained to be original constituents.

[2] *Bull. S. G. F.* 3rd ser. iii. 199. See also Fouqué and Michel-Lévy, 'Minéralogie Micrographique,' p. 189. Some eruptive rocks abound in corroded or somewhat rounded or broken crystals which obviously have belonged to some previous state of consolidation. Such crystals, which are obviously more ancient than those forming the general mass of the rock, have been called *allogenic*, while those which belong to the time of formation of the rock, or to some subsequent change within the rock, are known as *authigenic*.

illustrations of the original separation of mineral ingredients from the general magma of a rock (see p. 205).

In some cases minerals assume a concretionary shape, which may be observed chiefly though not entirely in rocks formed in water. Some minerals are particularly prone to occur in concretions (p. 135). Siderite (ferrous carbonate) is to be found in abundant nodules, mixed with clay and organic matter among consolidated muddy deposits (p. 187). Calcite (calcium-carbonate) is likewise abundantly concretionary (pp. 176, 190). Silica, as chert and flint, appears in calcareous formations in irregular concretions, derived mainly from the remains of marine organisms (pp. 179, 625). Phosphatic and glauconitic concretions are also common (pp. 180, 181, 626, 627).

Secondary minerals have been developed as the result of subsequent changes in rocks, and are almost invariably due to the chemical action of percolating water, either from above or from below. Occurring under circumstances in which such water could act with effect, they are found in cracks, joints, fissures and other divisional planes and cavities of rocks, especially in the minute interspaces between the component grains or minerals. Subterranean channels, frequently several feet or even yards wide, have been gradually filled up by the deposit of mineral matter on their sides (see the Section on Mineral Veins). The cavities formed by expanding steam in ancient lavas (amygdaloids) have offered abundant opportunities for deposits of this kind, and have accordingly been in large measure occupied by secondary minerals (amygdales), as calcite, chalcedony, quartz and zeolites.

In the following list of the more important rock-forming minerals, attention is drawn mainly to those of their features that possess geological importance; the physical, chemical and microscopic characters of these minerals will be found in a text-book of mineralogy or petrography. Reference is therefore made here to features of more particular significance to the geologist, such as modes of occurrence, whether original or secondary; modes of origin, whether igneous, aqueous, or organic; pseudomorphs, that is, the various minerals which any given mineral has replaced, while retaining their external forms, and likewise those which are found to have supplanted the mineral in question while in the same way retaining its form—a valuable clue to the internal chemical changes which rocks undergo from the action of percolating water (Book III. Part II. Sect. ii. §§ 1 and 2); and lastly, characteristics or peculiarities of weathering, where any such exist that deserve special mention.

1. NATIVE ELEMENTS are comparatively of rare occurrence, and only two of them, Carbon and Sulphur, occasionally play the part of noteworthy essential and accessory constituents of rocks. A few of the native metals, more especially copper and gold, now and then appear in sufficient quantity to constitute commercially important ingredients of veins and rock-masses.

Carbon occurs uncombined in two forms—the Diamond and Graphite.

**Diamond.**—This gem is of much geological interest in regard to its origin and its bearing upon the history of the carbon in the earth's crust. It has chiefly been obtained from alluvial deposits derived from the degradation of various crystalline rocks, but is now found in the matrix of certain volcanic agglomerates in South Africa, where, however,

it occurs as one of the constituents derived from the explosion of igneous material at some depth beneath the surface. Recently the mineral has been detected by Professor Bonney in an eclogite fragment from the agglomerate, which is thus found to be here its parent-rock.[1] By a series of carefully devised experiments, M. Moissan has succeeded in producing small diamonds artificially by fusing iron rich in carbon under pressure, and allowing it to cool, when the excess of carbon separated in minute clear crystals. Subsequently Dr. Friedländer fused a piece of olivine in a gas blow-pipe and stirred it with a little rod of graphite. After solidification the silicate was found to contain a great many microscopic crystals which, from their octahedral and tetrahedral forms, and their characteristic behaviour with reagents, he concluded to be diamond.[2]

**Graphite** occurs crystallised in small hexagonal plates, more frequently in foliated lumps and bands, or in compact aggregates (graphitite), or in dull massive and even earthy varieties (granitoid). It is found in ancient crystalline rocks, as gneiss, mica-schist, granite, &c.; some of the Laurentian limestones of Canada being so full of the diffused mineral as to be profitably worked for it. In some instances coal and coal-plants have been observed changed into graphite by intrusive igneous rocks (granite, gneiss, basalt), as in the Carboniferous rocks of the eastern and central Alps, and in the coal-field of Ayrshire. Among ancient crystalline, especially eruptive, rocks and in meteorites, its presence may be due to the decomposition of metallic carbides. Graphite may frequently be observed as a kind of black dust aggregated in the centre of minerals that have been developed in a sedimentary rock (shale, slate, &c.) by contact metamorphism, as in andalusite and chiastolite, and sometimes in quartz and garnet. Occasionally it occurs as a pseudomorph after calcite and pyrites, and sometimes encloses sphene and other minerals.[3]

**Sulphur** occurs in a native state, 1st, as a product of volcanic action in the vents and fissures of active and dormant cones. Volcanic sulphur is formed from the oxidation of the sulphuretted hydrogen, so copiously emitted with the steam that issues from volcanic vents, as at the typical Solfatara, near Naples. It may also be produced by the mutual decomposition of the same gas and anhydrous sulphuric acid. 2nd, in beds and layers, or diffused particles, resulting from the alteration of previous minerals, particularly sulphates; 3rd, in some mineral springs through the decomposition of the sulphuretted hydrogen in the thermal water. When formed at high temperatures, as in solfataras, this mineral probably crystallises at first in monoclinic forms, but these are unstable and subsequently pass into the usual orthorhombic forms in which natural sulphur is found. These natural crystals melt at a temperature not much above that of boiling water (238·1° Fahr.). The formation of sulphur may be observed in progress at many sulphureous springs, where it falls to the bottom as a pale mud through the oxidation of the sulphuretted hydrogen in the water. The mineral occurs in Sicily, Spain and elsewhere, in beds of bituminous limestone and gypsum. These strata, sometimes full of remains of fresh-water shells and plants, are interlaminated with sulphur, the very shells being not infrequently replaced by it. Here the presence of the sulphur may be traced

[1] See M. Chaper, 'Sur la Région diamantifère de l'Afrique australe,' Paris, 1880; L. De Launay, 'Les Diamants du Cap,' Paris, 1897; Max Bauer, 'Edelsteinkunde,' Leipzig, 1896; H. Carvill Lewis, 'Papers and Notes on the Genesis and Matrix of the Diamond,' London, 1897; Professor Bonney, *Geol. Mag.* 1895, p. 492; 1897, pp. 448, 497; 1899, p. 309; 1900, p. 246; and *Proc. Roy. Soc.* lxv. (1899), p. 223; lxvii. (1900), p. 475; O. A. Derby, "Brazilian Evidence on the Genesis of the Diamond," *Journ. Geol.* vi. p. 121.

[2] *Geol. Mag.* 1898, p. 226.

[3] Vom Rath, *Sitzungsb. Wien. Akad.* x. p. 67; Sullivan in Jukes' 'Manual of Geology,' 3rd edit. (1872), p. 72; E. Weinschenk, *Abhandl. Akad.* Munich, ii. cl. xix 2te Abth. (1897). *Op. cit.* 1900. *Comptes rendus du Congrès Géol. Internat. Paris*, 1901, i. p. 447; *Zeitsch. prakt. Geol.* 1900, pp. 36, 174 (see also *postea*, p. 186, and Book III. Part I. Sect. i. § 2).

to the reduction of the calcium-sulphate to the state of sulphide, through the action of the decomposing organic matter, and the subsequent production and decomposition of sulphuretted hydrogen, with consequent liberation of sulphur.[1] The sulphur deposits of Sicily furnish an excellent illustration of the alternate deposit of sulphur and limestone. They consist mainly of a marly limestone, through which the sulphur is partly disseminated and partly interstratified in thin laminæ and thicker layers, some of which are occasionally 28 feet deep. Below these deposits lie older Tertiary gypseous formations, the decomposition of which has probably produced the deposits of sulphur in the overlying more recent lake basins.[2] The weathering of sulphur is exemplified on a considerable scale at these Sicilian deposits. The mineral, in presence of limestone, oxygen and moisture, becomes sulphuric acid, which, combining with the limestone, forms gypsum, a curious return to what was probably the original substance from the decomposition of which the sulphur was derived. Hence the site of the outcrop of the sulphur beds is marked at the surface by a white earthy rock, or "borscale," which is regarded by the miners in Sicily to be a sure indication of sulphur underneath, as the "gossan" of Cornwall is indicative of underlying metalliferous veins.[3]

**Iron**, the most important of all the metals, is chiefly found native in blocks which have fallen as meteorites, also in grains or dust enclosed in hailstones, in snow of the Alps, Sweden and Siberia, and in the mud of the ocean floor at remote distances from land. There can be no doubt that a small but constant supply of native iron (cosmic dust) is falling upon the earth's surface from outside the terrestrial atmosphere.[4] This iron is alloyed with nickel, and contains small quantities of cobalt, copper and other ingredients.

There can be no doubt, however, that native iron occurs as a terrestrial mineral, though somewhat rarely found. Half a century ago (1852), Dr. Andrews showed that native iron, in minute spicules or granules, exists in some basalts and other volcanic rocks,[5] and Mr. J. Y. Buchanan has detected it in appreciable quantity in the gabbro of the west of Scotland. It occurs also in the basalts of Bohemia and Greenland.[6] It has

[1] Braun, *Bull. S. G. F.*, 1e sér. xii. p. 171.

[2] *Mem. Real. Comit. Geol. d'Italia*, i. (1871).

[3] *Journ. Soc. Arts*, 1873, p. 170. E. Ledoux, *Ann. des Mines*, 7me sér. vii. p. 1. The Sicilian sulphur beds belong to the Oeningen stage of the Upper Tertiary deposits. They contain numerous plants and some insects. H. T. Geyler, *Palæontographica*, xxiii. Lief. 9, p. 317. Von Lasaulx, *Neues Jahrb.* 1879, p. 490. A. Stella, *Bull. Soc. Geol. Ital.* xix. (1900), p. 694. It may be added that sulphur is sometimes found associated with orpiment, realgar and many other minerals as a result of the spontaneous ignition of coal-seams. Lacroix, 'Minéralogie de la France,' tome ii. p. 368.

[4] See Ehrenberg, *Frorieps Notizen*, Feb. 1846. Nordenskiöld, *Comptes rendus*, lxxvii. p. 463, lxxviii. p. 236. Tissandier, *op. cit.* lxxviii. p. 821, lxxx. p. 58, lxxxi. p. 576. See lxxv. (1872), p. 683. Yung, *Bull. Soc. Vaudoise Sci. Nat.* (1876), xiv. p. 493. Ranyard. *Monthly Not. Roy. Astron. Soc.* xxxix. (1879), p. 161. T. L. Phipson, *Comptes rend.* lxxxiii. p. 364. A Committee of the British Association was appointed in 1880 to investigate the subject of cosmic dust. (See its reports for 1881-83.) Murray and Renard, *Proc. Roy. Soc. Edin.* 1884. *Report of Challenger Expedition*, "Deep Sea Deposits," and "Narrative of the Cruise of H.M.S. *Challenger*," ii. p. 809 (1885). This cosmic dust is further referred to, *postea*, p. 584.

[5] *Brit. Assoc. Rep.* 1852, *postea*, p. 457.

[6] Nordenskiöld described fifteen blocks of iron on the island of Disco, Greenland, the weight of the two largest being 21,000 and 8000 kilogrammes (20 and 8 tons, respectively). He observed that at the same locality, the underlying basalt contains lenticular and disc-shaped blocks of precisely similar iron, and he inferred that the whole of the blocks may belong to a meteoric shower which fell during the time (Tertiary) when the basalt was poured out at the surface. He dismissed the suggestion that the iron could possibly be of telluric origin (*Geol. Mag.* ix, 1872, p. 462 ; *Compt. rend.* 1893, p. 677). But the microscope reveals in this basalt the presence of minute particles of native iron which, associated with viridite, are moulded

likewise been found without any alloy of nickel among the Carboniferous sandstones and shales of Missouri.[1]

2. OXIDES. A few of the oxides occur by themselves as essential constituents or frequent ingredients of rocks. Especially is this the case with the oxides of silicon and iron. The great majority of the oxides, however, form compounds with some acid.

SILICA ($SiO_2$) is found in three chief forms, Quartz, Tridymite, and Opal.

**Quartz** is abundant as (1) an original and essential constituent of many eruptive rocks (granite, rhyolite or quartz-trachyte, and quartz-porphyry); of many metamorphic rocks (gneiss, mica-schist, quartzite) and of a large number of derivative or sedimentary rocks (sandstone, conglomerate, greywacke); (2) a secondary ingredient, wholly or partially filling veins, joints, cracks, and cavities. It has been produced from (*a*) igneous action, as in many volcanic rocks; (*b*) aquo-igneous, or metamorphic action, as in gneisses, &c.; (*c*) solution in water, as where it lines cavities or replaces other minerals. As silica is held in solution sometimes in notable quantity in hot water, it commonly occurs in thermal springs, and it has thus been abundantly introduced into the pores, cavities and fissures of rocks. This last mode of formation is that of the crystallised quartz and chalcedony so often found as secondary ingredients.

The study of the endomorphs and pseudomorphs of quartz is of great importance in the investigation of the history of rocks. No mineral is so conspicuous for the variety of other minerals enclosed within it. In some secondary quartz-crystals, each prism forms a small mineralogical cabinet enclosing a dozen or more distinct minerals, as rutile, hæmatite, limonite, pyrites, chlorite, and many others.[2] Quartz may be observed replacing calcite, aragonite, siderite, gypsum, rock-salt, hæmatite, &c. This facility of replacement makes silica one of the most valuable petrifying agents in nature. Organic bodies which have been silicified retain, often with the utmost perfection, their minutest and most delicate structures.

Quartz may usually be identified by its external characters, and especially by its vitreous lustre and hardness. When in the form of minute blebs or crystals, it may be recognised in many rocks with a good lens. Under the microscope, it presents a characteristic brilliant chromatic polarisation, and in convergent light gives a black cross. Where it is an original and essential constituent of a rock, quartz very commonly contains minute rounded or irregular cavities or pores, partially filled with liquid (*postea*, p. 143). So minute are these cavities that a thousand millions of them may, when they are closely aggregated, lie within a cubic inch. The liquid is chiefly water, not uncommonly containing sodium chloride or other salt, sometimes liquid carbon-dioxide and hydrocarbons.[3]

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round the crystals of labradorite and augite (Fouqué and Michel-Lévy, 'Minéral. Micrograph.' p. 443). Steenstrup, Daubrée, and others appear therefore to be justified in regarding this iron as derived from an inner portion of the globe, which lies at depths inaccessible to our observations, but from which the vast Greenland basalt eruptions have brought up traces to the surface (K. J. T. Steenstrup, *Vid. Medd. Nat. Fören.* Copenhagen (1875), No. 16-19, p. 284; *Geol. Fören. Stockholm Forhandl.* xiv. (1892), p. 312; *Z. D. G. G.* xxviii. (1876), p. 225; *Mineralog. Mag.* July 1884. F. Wöhler, *Neues Jahrb.* 1879, p. 832. Daubrée, *Discours Acad. Sci.* 1 March 1880, p. 17. W. Flight, *Geol. Mag.* ii. (2nd ser.), p. 152. Winkler, *Öfversigt. K. Vet. Akad. Förhandl.*, Stockholm, 1901, No. 7, pp. 495, 505. See also the papers already cited on p. 16.

[1] E. T. Allen, *Amer. Journ. Sci.* iv. (1897), p. 99.

[2] See Sullivan, in Jukes' 'Manual of Geology,' 3rd edit. (1872), p. 61.

[3] See Brewster, *Trans. Roy. Soc. Edin.* x. p. 1. Sorby, *Quart. Journ. Geol. Soc.* xiv. p. 453. *Proc. Roy. Soc.* xv. p. 153; xvii. p. 299. Zirkel, 'Mikroskopische Beschaffenheit der Mineralien und Gesteine,' p. 39. Rosenbusch, 'Mikroskopische Physiographie,' i. p. 30. Hartley, *Journ. Chem. Soc.* February 1876. The occurrence of fluid-cavities in the crystals of rocks is more fully described at p. 143.

Rock-crystal and crystalline quartz resist atmospheric weathering with great persistence. Hence the quartz-grains may usually be easily discovered in the weathered crust of a quartziferous igneous rock. But corroded quartz-crystals have been observed in exposed mountainous situations. with their edges rounded and eaten away.[1]

Certain compact, opaque or translucent siliceous minerals, such as chalcedony, flint and jasper, have generally been regarded as non-crystalline and more or less impure forms of quartz. Recent researches, with the use of thin slices of the minerals and the microscope, have shown, however, that they are in large part formed of fibrous crystalline silica mingled with a variable proportion of opal. They appear to be generally if not always the results of deposition from water, and are to be regarded as secondary products. They occur in threads and veins traversing eruptive metamorphic and sedimentary rocks, and sometimes as a matrix in which the grains of a rock are enclosed. Some of them are also found as concretions and irregular lumps, like the flints of the Chalk (*postea*, p. 179). This group of siliceous minerals is more easily affected by processes of decay than quartz. Flint and many forms of coloured chalcedony weather with a white crust. But it is chiefly from the weathering of silicates (especially through the action of organic acids) that the soluble silica of natural waters is derived. (Book III. Part II. Sect. iii. § 1).

**Tridymite** has been met with chiefly among volcanic rocks (trachytes, andesites, &c.) both as an abundant constituent of those which have been poured out in the form of lava, and also in ejected blocks (Vesuvius).[2]

**Opal**, a hydrous condition of silica formed from solution in water, is usually disseminated in veins and nests through rocks. Semi-opal occasionally replaces the original substance of fossil wood (wood-opal). Several forms of opal are deposited by geysers, and are known under the general appellation of Sinters. Closely allied to the opals are the forms in which hydrous (soluble) silica appears in the organic world, where it constitutes the frustules of diatoms, the skeletons of radiolaria, &c. Tripoli powder (Kieselguhr), randanite, and other similar earths, are composed mainly or wholly of the remains of diatoms, &c.

**Corundum**, aluminium-oxide, is found as the gems Sapphire and Ruby, more commonly in colourless, blue, brown, or red forms known as Corundum, and sometimes in the dull, finely granular variety called Emery. It is not an essential constituent of rocks, but it presents itself commonly associated with spinel, rutile and sillimanite in eruptive rocks, especially granites, lamprophyres and peridotites, in crystalline schists, and in rocks altered by contact with granite, such as limestones and dolomites. In the eruptive rocks it appears sometimes to have separated out of an original magma containing sufficient alumina, but sometimes to have been supplied from clay-rock, fragments of which may have been carried up in a magma deficient in alumina. Of the latter condition an example has been cited from Yogo Gulch, Montana, where a dark basic lamprophyre, consisting mainly of biotite and pyroxene, contains well-crystallised sapphires. In zones of contact metamorphism it has been developed in aluminous rocks by the action of the intrusive material[3] (Book IV. Part VIII. Sects. ii. and iii.).

[1] Roth, *Chem. Geol.* i. p. 94.

[2] Vom Rath, *Z. D. G. G.* xxv. p. 236, 1873.

[3] On the occurrence and origin of corundum, consult T. M. Chatard, *Bull. U. S. G. S.* No. 42 (1887), pp. 45-54; F. P. King, "The Corundum Deposits of Georgia," *Bull. Geol. Surv. Georgia*, No. 2. (1894); Lagorio, *Zeitsch. Kryst.* xxiv. (1895), p. 285; Morozewicz, *Zeitsch. Kryst.* xxiv. (1895), p. 280; *Tschermak's Mittheil.* xviii. (1898), pp. 1-105; "Mineral Resources of United States," in *17th Ann. Rep. U. S. G. S.* (1896); Miller, *Report of Bureau of Mines*, Ontario, 1899, pp. 205, 250; Pirsson, *20th Ann. Rep. U. S. G. S.* (1900), p. 552; Busz, *Geol. Mag.* 1896, p. 492; J. J. H. Teall, *Summary of Progress Geol. Survey of United Kingdom*, 1898, p. 87; Coomára Swámy, *Q. J. G. S.* lvii. (1901), p. 185; J. H. Pratt, *Amer. Jour. Sci.* vi. (1898), p. 49, vii. (1899), p. 281, viii. (1899), p. 227; 'Manual of Geology of India,' 2nd edit. Part I. Corundum, by T. H. Holland, 1898.

IRON OXIDES.—Four minerals, composed mainly of iron oxides, occur abundantly as essential and accessory ingredients of rocks: Hæmatite, Limonite, Magnetite, and Titanic iron.

**Hæmatite** (Fer oligiste, Rotheisenerz, Eisenglanz, $Fe_2O_3$=Fe70, O30) in the crystallised form occurs in veins, as well as lining cavities and fissures of rocks. The fibrous and more common form (which often has portions of its mass passing into the crystallised condition) lies likewise in strings or veins; also in cavities, which, when of large size, have given opportunity for the deposit of great masses of hæmatite, as in cavernous limestones (Westmoreland). It occurs with other ores and minerals as an abundant component of mineral veins, likewise in beds interstratified with sedimentary or schistose rocks. Scales and specks of opaque or clear bright red hæmatite, of frequent occurrence in the crystals of rocks, give them a reddish colour or peculiar lustre (perthite, stilbite). Hæmatite appears abundantly as a product of sublimation in clefts of volcanic cones and lava streams, and it is found as an accessory constituent in some eruptive rocks. But it is probably in most cases a deposition from water, resulting from the alteration of some previous soluble combination of the metal, such as the oxidation of the sulphate. It occurs in veins and beds, and as the earthy pigment that gives a red colour to sandstones, clays and other rocks. It is found pseudomorphous after ferrous carbonate, and this has probably been the origin of beds of red ochre occasionally intercalated among stratified rocks. It likewise replaces calcite, dolomite, quartz, barytes, pyrites, magnetite, rock-salt, fluor-spar, &c.

**Limonite** (Brown iron-ore, $2Fe_2O_3+3H_2O=Fe_2O_3$ 85·56, $H_2O$ 14·44) occurs in beds among stratified formations, and may be seen in the course of deposit, through the action of organic acids, on marsh-land (bog-iron-ore) and lake-bottoms. (Book IV. Part II. Sect. iii.) In the form of yellow ochre, it is precipitated from the waters of chalybeate springs containing green vitriol derived from the oxidation of iron-sulphides.[1] It is a common decomposition product in rocks containing iron among their constituents. It is thus always a secondary or derivative substance, resulting from chemical alteration. It is the usual pigment which gives tints of yellow, orange and brown to rocks. The pseudomorphous forms of limonite show to what a large extent combinations of iron are carried in solution through rocks. The mineral has been found replacing calcite, siderite, dolomite, hæmatite, magnetite, pyrite, marcasite, galena, blende, gypsum, barytes, fluor-spar, pyroxene, quartz, garnet, beryl, &c.

**Magnetite** (Fer oxydulé, Magneteisen, $Fe_3O_4$) occurs abundantly in some schists, in scattered octohedral crystals; in crystalline massive rocks like granite, in diffused grains or minute crystals; among some schists and gneisses (Norway and the eastern states of North America), in massive beds; in basalt and other volcanic rocks, as an essential constituent, in minute octohedral crystals, or in granules or crystallites. It is likewise found as a pseudomorphous secondary product, resulting from the alteration of some previous mineral, as olivine, hæmatite, pyrite, quartz, hornblende, augite, garnet and sphene. It occurs with hæmatite, &c., as a product of sublimation at volcanic foci, where chlorides of the metals in presence of steam are resolved into hydrochloric acid and anhydrous oxides. It may thus result from either aqueous or igneous operations. It is liable to weather by the reducing effects of decomposing organic matter, whereby it becomes a carbonate, and then by exposure passes into the hydrous or anhydrous peroxide. The magnetite grains of basalt-rocks are very generally oxidised at the surface, and sometimes even for some depth inward.

**Titanic Iron** (Titaniferous Iron, Menaccanite, Ilmenite, Fer titané, Titaneisen, $FeTiO_3$) occurs in scattered grains, plates and crystals as an abundant constituent of many crystalline rocks (basalt-rocks, diabase, gabbro and other igneous masses); also in veins or beds in syenite, serpentine and metamorphic rocks;[2] scarcely to be distinguished

[1] Sullivan, Jukes' 'Manual of Geology,' p. 68.

[2] Some of the Canadian masses of this mineral are 90 feet thick and many yards in length.

from magnetite when seen in small particles under the microscope, but possessing a brown semi-metallic lustre with reflected light; resists corrosion by acids when the powder of a rock containing it is exposed to their action, while magnetite is attacked and dissolved. Titanic iron frequently resists weathering, so that its black glossy granules project from a weathered surface of rock. In other cases, it is decomposed either by oxidation of its protoxide, when the usual brown or yellowish colour of the hydrous ferric oxide appears, or by removal of the iron. The latter is believed to be the origin of a peculiar milky white opaque substance, frequently to be observed under the microscope, surrounding and even replacing crystals of titanic iron, and named Leucoxene by Gümbel.[1] In other cases the decomposition has resulted in the production of sphene.[2]

**Chromite** ($FeCr_2O_4$) occurs in black opaque grains and small octahedral crystals, not infrequently in altered olivine-rocks; a valuable mineral, as the source of the chrome pigments. It is obtained from Maryland, North Carolina, Norway, New South Wales, &c.[3]

**Spinels**, a group of minerals, may be taken here. They are closely related to each other, having cubic forms and varying in composition from *magnetite* (see above) at the one end to true *spinel* ($MgAl_2O_4$) at the other. They are not infrequent as minute grains or crystals in some igneous and metamorphic rocks, being specially developed among the peridotites, where also they are sometimes associated with the free oxide of aluminium (corundum). True spinel occurs in association with malacolite, coccolite and other minerals in the crystalline limestone of Glenelg, Scotland. Between magnetite and spinel come intermediate varieties, as *Chromite* (see above), *Picotite*, *Hercynite* and *Pleonaste*.

MANGANESE OXIDES, as already mentioned, are frequently associated with those of iron in ordinary rock-forming minerals, but in such minute proportions as to have been generally neglected in analyses. Their presence in the rocks of a district is sometimes shown by deposits of the hydrous oxide in the forms of Psilomelane ($H_2MnO_4+H_2O$) and Wad ($MnO_2+MnO+H_2O$). These deposits sometimes form black or dark brown branching, plant-like or *dendritic* impressions between the divisional planes of close-grained rocks (limestone, felsite, &c.); sometimes they appear as accumulations of a black or brown earthy substance in hollows of rocks, occasionally as deposits in marshy places, like those of bog-iron-ore, and abundantly on some parts of the sea-floor.[4]

SILICATES.—These embrace by far the largest and most important series of rock-forming minerals, seeing that by themselves they constitute at least nine-tenths of the terrestrial crust, and make up practically all the rocks except the sandstones, quartzites and carbonates.[5] Their chief groups are the anhydrous aluminous and magnesian

[1] 'Die Paläolitische Eruptivgesteine des Fichtelgebirges,' 1874, p. 29. See Rosenbusch, *Mik. Physiog.* ii. p. 336. De la Vallée Poussin and Renard, *Mém. Couronn. Acad. Roy. Belg.*, 1876, xl. Plate vi. pp. 34 and 35. Fouqué and Michel-Lévy, 'Minéralogie Micrograph.' p. 426. See *postea*, p. 618.

[2] The recognition of Titanic Iron in basic eruptive rocks has been the subject of prolonged investigation by Professor J. H. L. Vogt of Christiania. See his papers in *Geol. Fören. Förhandl.*, Stockholm, 1891; *Zeitsch. Prakt. Geol.* 1893, p. 6; 1894, p. 382; 1900, p. 233; 1901, pp. 9, 180, 289, 327.

[3] On the occurrence, origin and chemical composition of Chromite, J. H. Pratt, *Trans. Amer. Inst. Min. Engin.* February 1899.

[4] See the paper of Mr. Penrose already cited (*ante*, p. 85), and *postea*, p. 585.

[5] See the important researches by F. W. Clarke and E. A. Schneider, "Experiments upon the Constitution of the Natural Silicates," *Amer. Jour. Sci.* xl. (1890), pp. 303-312, 405-415, 452-457; F. W. Clarke, "The Chemical Structure of the Natural Silicates," *Bull. U. S. G. S.* No. 60 (1890), p. 13, and No. 125 (1895), p. 109. The last-cited paper is specially deserving of the attention of the student.

silicates, embracing the Felspars, Hornblendes, Augites, Micas, &c., and the hydrous silicates, which include the Zeolites, Clays, talc, chlorite, serpentine, &c.

The family of the Felspars forms one of the most important of all the constituents of rocks, seeing that its members constitute by much the largest portion of the plutonic and volcanic rocks, are abundantly present among many crystalline schists, and by their decay have supplied a great part of the clay out of which argillaceous sedimentary formations have been constructed.

The felspars are usually divided into two series. 1st, The monoclinic felspars, consisting of two species or varieties, Orthoclase and Sanidine; and 2nd, The triclinic felspars, among which, as constituents of rocks, may be mentioned the potash species microcline and the group of the plagioclase felspars comprising albite, anorthite, oligoclase, andesine, and labradorite.[1]

**Orthoclase** (Orthose, $K_2O$ 16·89, $Al_2O_3$ 18·43, $SiO_2$ 64·68) occurs abundantly as an original constituent of many crystalline rocks (granite, syenite, rhyolite, gneiss, &c.), likewise in cavities and veins in which it has segregated from the surrounding mass (pegmatite); seldom found in unaltered sedimentary rocks except in fragments derived from old crystalline masses; generally associated with quartz, and often with hornblende, while the felspars less rich in silica more rarely accompany free quartz. It is an original constituent of plutonic and old volcanic rocks (granite, felsite, &c.), and of gneiss and various schists. A few examples have been noticed where it has replaced other minerals (prehnite, analcime, laumontite). Under the microscope it is recognisable from quartz by its characteristic rectangular forms, cleavage, twinning, angle of extinction, turbidity, and frequent alteration. Orthoclase weathers on the whole with comparative rapidity, though durable varieties are known. The alkali and some of the silica are removed, and the mineral passes into clay or kaolin (p. 167).

Sanidine, the clear glassy fissured variety of orthoclase so conspicuous in the more silicated Tertiary and modern lavas, occurs in some trachytes in large flat tables (hence the name "sanidine"); more commonly in fine clear or grey crystals or crystalline granules; an eminently volcanic mineral, specially characteristic of the rhyolites.

**Triclinic Felspars.**—While the different felspars which crystallise in the triclinic system may be more or less easily distinguished in large crystals or crystalline aggregates, they are difficult to separate in the minute forms in which they commonly occur as rock constituents. One of them, known as Microcline, is identical in composition with orthoclase, and is thus distinguished from all the other triclinic forms in being a potash variety. It is so closely similar to Orthoclase that the two minerals cannot always be discriminated. The minute researches of Des Cloiseaux, however, proved them to belong to two distinct systems of crystallisation, and placed Microcline as a new species in the triclinic series.[2] This felspar occurs in many granites, and forms the common variety in the graphic condition of these rocks. It is found likewise in gneisses and other old crystalline schists, and also in limestones altered by contact with lherzolite. Another allied felspar called Anorthose has been classed with Microcline as a group of pseudo-monoclinic forms, on account of their close resemblance to Orthoclase, which they frequently accompany or replace. Anorthose contains from 7 to 10 per cent of soda, besides potash. It is found in granites and syenites, in some phonolites, trachytes and andesites.

[1] See A. Des Cloiseaux, *Ann. des Mines;* G. Tschermak, "Die Feldspathgruppe," *Sitzb. Akad. Wien.* 1864; C. E. Weiss, 'Beiträge zur Kenntniss der Feldspathbildung,' Haarlem, 1866; F. Fouqué, "Contributions à l'Étude des Feldspaths des Roches Volcaniques," *Bull. Soc. Française Min.* tome xvii. (1894), and separately printed, p. 336; A. Michel-Lévy, 'Étude sur la Détermination des Feldspaths dans les Plaques minces,' Paris, 1894, p. 109; Fouqué and Michel-Lévy, 'Minéral. Micrograph.' 1878, pp. 209, 227; A. Lacroix, 'Minéralogie de la France,' tome ii. pp. 23-202; N. H. Winchell. *Amer. Geol.* xxi. (1898), pp. 12-49.

[2] *Ann. Chim. et Phys.* 5me sér. tome ix. (1876); *Compt. rend.* lxxxii. p. 885.

The other triclinic felspars have been grouped by petrographers under the general name Plagioclase (with oblique cleavage), proposed by Tschermak, who regards them as mixtures in various proportions of two fundamental compounds—albite or soda-felspar, and anorthite or lime-felspar.[1]

They occur in well-developed crystals, and also in irregular crystalline grains, crystallites or microlites. On a fresh fracture, their crystals often appear as clear glassy strips, on which may usually be detected a fine parallel lineation or ruling, indicating a characteristic polysynthetic twinning which never appears in orthoclase. A felspar striated in this manner can thus be at once pronounced to be a triclinic form, though the distinction is not invariably present. Under the microscope, the fine parallel lamellation or striping, best seen with polarised light, forms one of the most distinctive features of this group of felspars. The chief plagioclase felspars are, Albite (soda-felspar, $Na_2O$ 11·82, $Al_2O_3$ 18·56, $SiO_2$ 68·62), found in some granites, and in several volcanic rocks; soda-lime and lime-soda felspars, as Oligoclase ($Na_2O$ 8·2, CaO 4·8, $Al_2O_2$ 23·0, $SiO_2$ 62·8), which occurs in many granites and other eruptive rocks; Andesine ($Na_2O$ 7·7, CaO 7·0, $Al_2O_3$ 25·6, $SiO_2$ 60·0) in some syenites, &c.; Labradorite ($Na_2O$ 4·6, CaO 12·4, $Al_2F_3$ 30·2, $SiO_2$ 52·9), an essential constituent of many lavas, &c., abundant in masses in the azoic rocks of Canada, &c.; Anorthite (lime-felspar, CaO 20·10, $Al_2O_3$ 36·82, $SiO_2$ 43·08), found in many volcanic rocks, sometimes in granites and metamorphic rocks.

The triclinic felspars have been produced sometimes directly from igneous fusion, as can be studied in many lavas, where often one of the first minerals to appear in the devitrification of the original molten glass has been the labradorite or other plagioclase. The large beds as well as abundant diffused strings, veinings, and crystals of triclinic felspar (labradorite), which form a marked feature among the ancient gneisses of Eastern Canada, were probably originally masses of eruptive rock that have undergone alteration from the operation of the processes to which the formation of the crystalline schists was due. The more highly silicated species (albite, oligoclase) occur with orthoclase as essential constituents of many granites and other plutonic rocks. The more basic forms (labradorite, anorthite) are generally absent where free silica is present; but occur in the more basic igneous rocks (basalts, &c.).

Considerable differences are presented by the triclinic felspars in regard to weathering. On an exposed face of rock they lose their glassy lustre and become white and opaque. This change, as in orthoclase, arises from loss of bases and silica, and from hydration. Traces of carbonates may often be observed in weathered crystals. The original steam-cavities of old volcanic rocks have generally been filled with infiltrated minerals from the decomposition of the triclinic felspars during the volcanic period or by later weathering. Calcite, prehnite, and the family of zeolites have been abundantly produced in this way. The student will usually observe that where these minerals abound in the cells and crevices of a rock, the rock itself is for the most part proportionately decomposed, showing the relation that subsists between infiltration-products and the decomposition of the surrounding mass. Abundance of calcite in veins and cavities of a felspathic rock affords good ground for suspecting the presence in the latter of a lime felspar.[2] (See under "Albitisation," Book IV. Part VIII. Sect. ii.)

Saussurite, formerly described as a distinct mineral species, is now found to be the result of the decomposition of felspars, which have thus acquired a dull white aspect and contain secondary crystallisations (zoisite) out of the decomposed substance of the original felspar. Such saussuritic felspars occur in varieties of gabbro and

[1] On the optical discrimination of the Plagioclases, see Michel-Lévy, *Bull. Soc. Française Min.* xviii. No. 3, 1895.

[2] A valuable essay on the stages of the weathering of triclinic felspar as revealed by the microscope was published by G. Rose in 1867, *Z. D. G. G.* xix. p. 276.

diorite. Under the microscope they present a confused aggregate of crystalline needles and granules imbedded in an amorphous matrix. (See *postea*, p. 232.)

**Leucite** ($K_2O$ 21·53, $Al_2O_3$ 23·50, $SiO_2$ 54·97) is a markedly volcanic mineral, occurring as an abundant constituent of many Tertiary and modern lavas, and in some varieties of basalt. Under the microscope, sections of this mineral are eight-sided or nearly circular, and very commonly contain enclosures of magnetite, &c., conforming in arrangement to the external form of the crystal or disposed radially.

**Nepheline** ($Na_2O$ 17·04, $Al_2O_3$ 35·26, $K_2O$ 6·46, $SiO_2$ 41·24), essentially a volcanic mineral, being an abundant constituent of phonolite, of some Vesuvian lavas, and of some forms of basalt, presents under the microscope various six-sided and even four-sided forms, according to the angles at which the prisms are cut.[1] Under the name of *Elæolite* are comprised the greenish or reddish, dull, greasy-lustred, compact or massive varieties of nepheline, which occur in some syenites and other ancient crystalline rocks, and stand towards the clear varieties, very much as orthoclase does to sanidine.

THE MICA FAMILY[2] embraces a number of minerals, distinguished especially by their very perfect basal cleavage, whereby they can be split into remarkably thin elastic laminæ, and by a predominant splendent pearly lustre. They consist essentially of silicates of alumina, magnesia, iron and alkalies, and may be conveniently divided into two groups, the *white micas,* which are silicates of alumina with alkalies and iron, but with little or no magnesia, and the *black micas,* in which the magnesia and iron play a more conspicuous part.[3]

The first group includes Muscovite, Lepidolite and Paragonite ; the second contains Biotite, Phlogopite and Zinnwaldite.

**Muscovite** (Potash-mica, white mica, rhombic mica, Glimmer, $K_2O$ 3·07–12·44, $Na_2O$ 0–4·10, FeO 0–1·16, $Fe_2O_3$ 0·46–8·80, MgO 0·37–3·08, $Al_2O_3$ 28·05–38·41, $SiO_2$ 43·47–51·73, $H_2O$ 0·98–6·22), abundant as an original constituent of many eruptive rocks (granite, &c.) ; as one of the characteristic minerals of the crystalline schists ; as a product of regional and contact metamorphism, and in many sandstones, shales and other sedimentary strata, where its small parallel flakes, derived, like the surrounding quartz grains, from older crystalline masses, impart a silvery or "micaceous" lustre and fissility to the stone. The persistence of muscovite under exposure to weather is shown by the silvery plates of the mineral, which may be detected on a crumbling surface of granite or schist where most of the other minerals, save the quartz, have decayed ; also by the frequency of the micaceous lamination of sandstones and other clastic rocks.

Damourite, a hydrous variety of muscovite, occurs among crystalline schists. Sericite, another hydrous talc-like variety, occurs in soft inelastic scales in many schists, as a result of the alteration of orthoclase felspar.[4] Margarodite, a silvery talc-like hydrous mica, is widely diffused as a constituent of granite and other crystalline rocks.

**Lepidolite** (Lithia-mica), like muscovite, but with the potash partly replaced by lithia. It occurs in some granites and crystalline schists, especially in veins ; it is found in the tin-bearing granulites of Central France.

**Paragonite** (Soda-mica) forms the main mass of certain Alpine schists. It is

[1] On the microscopic distinction between nepheline and apatite, see Fouqué and Michel-Lévy, 'Minéral. Micrograph.' p. 276.

[2] See F. W. Clarke, "Studies in the Mica Groups," *Bull. U. S. G. S.* No. 55 (1889), p. 12, No. 42 (1887), p. 11, and No. 113 (1893), p. 22.

[3] See M. Baur, *Poggend. Ann.* cxxxviii. (1869), p. 337 ; Tschermak, *Sitzb. Akad. Wien.* lxxxvi. (1877), and lxxxviii. (1878) ; *Zeitsch. Kryst.* 1878, p. 14, and 1879, p. 122. On the microscopic determination of the micas, see Fouqué and Michel-Lévy, *op. cit.* p. 333, and Lacroix, 'Minéral. France,' i. p. 305.

[4] On the occurrence of this mineral in schists, see Lossen, *Z. D. G. G.* 1867, pp. 546, 661.

possible that many microscopic white micas of secondary origin and developed from the alteration of soda-bearing minerals (nepheline, triclinic felspars), hitherto classed as sericite, may belong to paragonite.[1]

**Biotite** (Magnesia-mica, black mica, hexagonal mica, MgO 10–30 per cent) occurs abundantly as an original constituent of many granites, gneisses, and schists; also sometimes in basalt, trachyte, and as ejected fragments and crystals in tuff. Its small scales, when cut transverse to the dominant cleavage, may usually be detected under the microscope by their remarkably strong dichroism, their fine parallel lines of cleavage and their frequently frayed appearance at the ends. Under the action of the weather it assumes a pale, dull, soft crust, owing to removal of its bases. The mineral *Rubellan*, which occurs in hexagonal brown or red opaque inelastic tables in some basalts and other igneous rocks, is regarded as an altered form of biotite.

Phlogopite, a mineral so closely allied to biotite as to be often indistinguishable from it, is found in the crystalline Archæan limestones. Its reddish-brown varieties all contain a little fluorine. Anomite is another mica of the same series.

Zinnwaldite (Lithionite) is a ferruginous mica containing lithia and fluorine found in the tin-bearing granites of Germany and Central France.

**Hornblende** (Monoclinic Amphibole, $CaO_2$ 10–12, MgO 11-24, $Fe_2O_3$ 0–10, $Al_2O_3$ 5–18, $SiO_2$ 40–50, also usually with some $Na_2O$, $K_2O$ and FeO). Divided into two groups. 1st, Non-aluminous, including the white and pale green or grey fibrous varieties (tremolite, actinolite, &c.). 2nd, Aluminous, embracing the more abundant dark green, brown, or black varieties. Under the microscope, hornblende presents cleavage-angles of 124° 30′, the definite cleavage-planes intersecting each other in a well-marked lattice work, sometimes with a finely fibrous character superadded. It also shows a marked pleochroism with polarised light, which, as Tschermak first pointed out, usually distinguishes it from augite.[2] Hornblende has abundantly resulted from the alteration (paramorphism) of augite (see below, Uralite). In many rocks the ferro-magnesian silicate which is now hornblende was originally augite; the epidiorites, for instance, were probably once dolerites or allied pyroxenic rocks. The pale non-aluminous hornblendes are found among gneisses, crystalline limestones, and other metamorphic rocks. The dark varieties, though also found in similar situations, sometimes even forming entire masses of rock (amphibolite, hornblende rock, hornblende-schist), are the common forms in granitic and volcanic rocks (syenite, diorite, hornblende-andesite, &c.). The former group naturally gives rise by weathering to various hydrous magnesian silicates, notably to serpentine and talc. In the weathering of the aluminous varieties, silica, lime, magnesia, and a portion of the alkalies are removed, with conversion of part of the earths and the iron into carbonates. The further oxidation of the ferrous carbonate is shown by the yellow and brown crust so commonly to be seen on the surface or penetrating cracks in the hornblende. The change proceeds until a mere internal kernel of unaltered mineral remains, or until the whole has been converted into a ferruginous clay.

Anthophyllite (Rhombic Amphibole $(MgFe)SiO_3$) is a mineral which occurs in bladed, sometimes rather fibrous forms, among the more basic parts of old gneisses; also in zones of alteration round some of the ferro-magnesian minerals of certain gabbros.

Soda-amphiboles resemble ordinary hornblende, but, as their name denotes, they contain a more marked proportion of soda. They include a blue variety called *Glaucophane*, which is found abundantly in certain schists; *Riebeckite*, which is also blue and occurs in some granites and micro-granites; *Arfvedsonite*, a dark greenish or brown variety.

Uralite is the name given to a mineral which was originally Pyroxene, but has

[1] Lacroix, 'Minéral. France,' tome i. p. 355.

[2] *Wien. Acad.* May 1869. See also Fouqué and Michel-Lévy, 'Minéral. Micrograph.' pp. 349, 365.

now by a process of paramorphism acquired the internal cleavage and structure of hornblende (amphibole). Under the microscope a still unchanged kernel of pyroxene may in some specimens be observed in the centre of a crystal surrounded by strongly pleochroic hornblende, with its characteristic cleavage and actinolitic needles (*postea*, p. 790). *Smaragdite* is a beautiful grass-green variety also resulting from the alteration of a pyroxene.

**Augite** (Monoclinic Pyroxene, CaO 12–27·5, MgO 3–22·5, FeO 1–34, $Fe_2O_3$ 0–10, $Al_2O_3$ 0–11; $SiO_2$ 40–57·5). Divided like hornblende into two groups. 1st, Non-aluminous, with a prevalent green colour (malacolite, coccolite, diopside, sahlite, &c.). 2nd, Aluminous, including generally the dark green or black varieties (common augite, fassaite). It would appear that the substance of hornblende and augite is dimorphous, for the experiments of Berthier, Mitscherlich and G. Rose showed that hornblende, when melted and allowed to cool, assumed the crystalline form of augite; whence it has been inferred that hornblende is the result of slow, and augite of comparatively rapid cooling.[1] Under the microscope, augite in thin slices is only very feebly pleochroic, and presents cleavage lines intersecting at an angle of 87° 5′. It is often remarkable for the amount of extraneous materials enclosed within its crystals. Like some felspars, augite may be found in basalt with merely an outer casing of its own substance, the core being composed of magnetite, of the ground-mass of the surrounding rock or of some other mineral (Fig. 11). The distribution of augite resembles that of hornblende; the pale, non-aluminous varieties are more specially found among gneisses, marbles, and other crystalline, foliated, or metamorphic rocks; the dark-green or black varieties enter as essential constituents into many igneous rocks of all ages, from Palæozoic up to recent times (diabase, basalt, andesite, &c.). Its weathering also agrees with that of hornblende. The aluminous varieties, containing usually some lime, give rise to calcareous and ferruginous carbonates, from which the fine interstices and cavities of the surrounding rock are eventually filled with threads and kernels of calcite and strings of hydrous ferric oxide. In basalt and dolerite, for example, the weathered surface often acquires a rich yellow colour from the oxidation and hydration of the ferrous oxide.

Omphacite, a granular variety of pyroxene, grass-green in colour, and commonly associated with red garnet in the rock known as eclogite.

Diallage, a variety of augite, characterised by its somewhat metallic lustre and foliated aspect, is especially a constituent of gabbro.

**Rhombic-Pyroxenes.**—There are three rhombic forms of pyroxene, which occur as important constituents of some rocks, Enstatite, Bronzite and Hypersthene. Enstatite occurs in lherzolite, serpentine, and other olivine rocks; also in meteorites. Bronzite is found under similar conditions to enstatite, from which it is with difficulty separable. It occurs in some basalts and in serpentines; also in meteorites. Bronzite and enstatite weather into dull green serpentinous products. Bastite or Schiller-spar is a frequent product of the alteration of Bronzite or Enstatite, and may be observed with its characteristic pearly lustre in serpentine. Hypersthene occurs in hypersthenite and hypersthene-andesite; also associated with other magnesian minerals among the crystalline schists.

A group of magnesian minerals crystallising in orthorhombic forms is embraced under the name of Peridots. Of these by far the most important as a rock-builder is Olivine.

**Olivine** (Chrysolite, MgO 32·4–50·5, FeO 6–29·7, $SiO_2$ 31·6–42·8) forms an essential ingredient of basalt, likewise the main part of various so-called olivine-rocks or peridotites (as lherzolite and picrite), and occurs in many gabbros. Under the microscope with polarised light it gives, when fresh, bright colours, specially red and green,

[1] The same results have been subsequently obtained by MM. Fouqué and Michel-Lévy, 'Synthèse des Minéraux et des Roches,' 1882, p. 78.

but it is not perceptibly pleochroic. Its orthorhombic outlines can sometimes be readily observed, but it often occurs in irregularly shaped granules or in broken crystals, and is liable to be traversed by fine fissures, which are particularly developed transverse to the vertical axis. It is remarkably prone to alteration. The change begins on the outer surface and extends inwards and specially along the fissures, until the whole is converted either into a green granular or fibrous substance, which is probably in most cases serpentine (Figs. 32 and 33), or into a reddish-yellow amorphous mass (limonite).

**Hauyne** ($SiO_2$ 34·06, $Al_2O_3$ 27·64, $Na_2O$ 11·79, $K_2O$ 4·96, CaO 10·60, $SO_4$ 11·25) occurs abundantly in Italian lavas, in basalt of the Eifel, and elsewhere.

**Nosean** ($SiO_2$ 33·79, $Al_2O_3$ 28·75, $Na_2O$ 26·20, $SO_4$ 11·26), under the microscope, is one of the most readily recognised minerals, showing a hexagonal or quadrangular figure, with a characteristic broad dark border corresponding to the external contour of the crystal, and where weathering has not proceeded too far, enclosing a clear colourless centre. It occurs in minute forms in most phonolites, also in large crystals in some sanidine volcanic rocks. Both hauyne and nosean are volcanic minerals associated with the lavas of more recent geological periods.

**Epidote** (Pistacite, CaO 16–30, MgO 0–4·9, $Fe_2O_3$ 7·5–17·24, $Al_2O_3$ 14·47–28·9, $SiO_2$ 33·81–57·65) occurs in many crystalline rocks, as a result of the alteration of other silicates such as felspars and hornblende (see *postea*, p. 790); largely distributed in certain schists and quartzites, sometimes associated with beds of magnetite and hæmatite.

**Zoisite** is allied to epidote but contains no iron (see Saussurite, p. 99). It occurs in altered basic igneous rocks and also (sometimes in large aggregations) in metamorphic groups.[1]

**Orthite** (Allanite), an aluminous silicate containing small quantities of some of the rarer metals (cerium, didymium, lanthanum, yttrium), occurs in small dispersed crystals in many granites.

**Vesuvianite** (Idocrase, CaO 27·7–37·5, MgO 0–10·6, FeO 0–16, $Al_2O_3$ 10·5–26·1, $SiO_2$ 35–39·7, $H_2O$ 0–2·73) occurs in ejected blocks of altered limestone at Somma, also among crystalline limestones and schists.

**Andalusite** ($Al_2O_3$ 50·96–62·2, $Fe_2O_3$ 0–5·7, $SiO_2$ 35·3–40·17); found in crystalline schists. The variety Chiastolite, abundant in some dark clay-slates, is distinguished by the regular manner in which the dark substance of the surrounding matrix has been enclosed, giving a cross-like transverse section. These crystals have been developed in the rock after its formation, and are regarded as proofs of contact-metamorphism. (Book IV. Part VIII.)

Sillimanite (Fibrolite), another form of the same composition as Andalusite, occurring in long straight needles, and also in minute interlaced fibres forming a compact rock, is of frequent occurrence among metamorphic rocks.

**Staurolite** ($SiO_2$ 26·32; $Al_2O_3$55·92; FeO 15·79; $H_2O$ 1·97), in many zones of contact metamorphism, is conspicuous in stumpy crystals and cross-shaped macles. Owing to its density, 3·34–3·77, it is easily separated from its matrix by means of heavy solutions. It is commonly associated with andalusite, cordierite and garnet.[2]

**Kyanite** (Disthene) occurs in bladed aggregates of a beautiful delicate blue colour among schistose rocks; also in granular forms. This mineral agrees in chemical composition with Andalusite and Sillimanite, and like them is generally the result of metamorphism.

**Cordierite** (Dichroite, Iolite, MgO 8·2–20·45, FeO 0–11·58, $Al_2O_3$ 28·72–33·11, $SiO_2$ 48·1–50·4, $H_2O$ 0–2·66) occurs as an alteration product of contact and regional

[1] On the optical properties of this mineral see E. H. Forbes, *Amer. Jour. Sci.* i. (1896), p. 26.

[2] On the chemical composition of Staurolite and the regular arrangement of its carbonaceous inclusions, S. L. Penfield and J. H. Pratt, *Amer. Jour. Sci.* xlvii. (1894), p. 81.

metamorphism in slates, gneiss, sometimes in large amount (cordierite-gneiss); occasionally as an accessory ingredient in some granites; also in talc-schist. Undergoes numerous alterations, having been found changed into pinite, chlorophyllite, mica, &c.

**Scapolites**, a series of minerals consisting of silicates of alumina, lime and soda, with a little chlorine. They are found among the cavities of lavas, but more frequently among metamorphic rocks, where they appear in association with altered felspars. Dipyre, Couseranite and Meionite are varieties of the series.

**Garnet** (CaO 0–5·78, MgO 0–10·2, $Fe_2O_3$ 0–6·7, FeO 24·82–39·68, MnO 0–6·43, $Al_2O_3$ 15·2–21·49, $SiO_2$ 35·75–52·11). The common red and brown varieties occur as essential constituents of eclogite, garnet-rock; and often as abundant accessories in mica-schist, gneiss, granite, &c., and in the zone of contact metamorphism around eruptive masses. Under the microscope, garnet as a constituent of rocks presents three-sided, four-sided, six-sided, eight-sided (or even rounded) figures according to the angle at which the individual crystals are cut; it is usually clear, but full of flaws or of cavities; passive in polarised light.

**Tourmaline** (Schorl, CaO 0–2·2; MgO 0–14·89, $Na_2O$ 0–4·95, $K_2O$ 0–3·59, FeO 0–12, $Fe_2O_3$ 0–13·08, $Al_2O_3$ 30·44–44·4, $SiO_2$ 35·2–41·16, B 3·63–11·78, F 1·49–2·58), with quartz, forms tourmaline-rock; associated with some granites; occurs also diffused through many gneisses, schists, crystalline limestones, and dolomites, likewise in sands (see Zircon). Pleochroism strongly marked.

**Zircon** ($ZrO_2$ 63·5–67·16, $Fe_2O_3$ 0–2, $SiO_2$ 32–35·26) occurs as a chief ingredient in the zircon-syenite of Southern Norway; frequent in granites, diorites, gneisses, crystalline limestones and schists; in eclogite; as clear red grains in some basalts, and also in ejected volcanic blocks; of common occurrence as clastic grains in sands, clays, sandstones, shales and other sedimentary rocks derived from crystalline masses, such as granite, &c.

**Titanite** (Sphene, CaO 21·76–33, $TiO_2$ 33–43·5, $SiO_2$ 30–35), dispersed in small characteristically lozenge-shaped crystals in many syenites, also in granite, gneiss, and in some volcanic rocks (basalt, trachyte, phonolite).

**Zeolites.**—Under this name is included a characteristic family of minerals, which have in most cases resulted from the alteration, and particularly from the hydration, of other minerals, especially of felspars. Secondary products, and only rarely original constituents of rocks, they often occur in cavities both as prominent amygdales and as vein-stones, and in minute interstices only perceptible by the microscope. In these minute forms they very commonly present a finely fibrous divergent structure. As already remarked (p. 99), a relation may often be traced between the containing rock and its enclosed zeolites. Thus among the basalts of the Inner Hebrides, the dirty green decomposed amygdaloidal sheets are the chief repositories of zeolites, while the firm, compact, columnar beds are comparatively free from these alteration products.[1] The formation of zeolites has been detected at the bottom of the deeper ocean abysses (*postea*, p. 585), likewise in the bricks traversed by the thermal waters of mineral springs (p. 475). Among the more common zeolites are *Analcite, Natrolite, Stilbite, Heulandite, Harmotome, Chabasite*, and *Apophyllite*. It has now been ascertained that Analcite is an original constituent of certain basic basalt-like igneous rocks, where it was originally mistaken for a glassy base. This mineral being isotropic in polarised light, cannot, when it shows no crystal forms, be distinguished from the volcanic glass, and it is possible that it may thus have a wider distribution as an original rock constituent than has been supposed.[2]

**Kaolin** ($Al_2O_3$ 38·6–40·7, CaO 0–·35, $K_2O$ 0–1·9, $SiO_2$ 45·5–46·53, $H_2O$ 9–14·54)

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[1] See Sullivan in Jukes' 'Manual of Geology,' p. 85.

[2] L. V. Pirsson, "On the Monchiquites or Analcite group of Igneous Rocks," *Journ. Geol.* iv. (1896), p. 679; Whitman-Cross, "An Analcite-basalt from Colorado," *op. cit.* v. (1897), p. 684.

results from the alteration of potash- and soda-felspars exposed to atmospheric, sometimes to solfataric, influences. Under the microscope the fine white powdery substance is found to include abundant minute six-sided colourless plates, scales, and monoclinic crystals (Kaolinite), which have been formed by re-crystallisation of the decomposed substance of the felspar. The purest white Kaolin is called *china-clay*, from its extensive use in the manufacture of porcelain. Ordinary clay is impure from admixture of iron, lime, and other ingredients, among which the débris of the undecomposed constituents of the original rock may form a marked proportion.

**Talc** (MgO 23·19–35·4, FeO 0–4·5, $Al_2O_3$ 0–5·67, $SiO_2$ 56·62–64·53, $H_2O$ 0–6·65) occurs as an essential constituent of talc-schist, and as an alteration product replacing mica, hornblende, augite, olivine, diallage, and other minerals in crystalline rocks.[1]

**Chlorite**, a group of soft, usually green silicates of alumina, magnesia and iron with more or less water (MgO 24·9–36, FeO 0–5·9, $Fe_2O_3$ 0–11·36, $Al_2O_3$ 10·5–19·9, $SiO_2$ 30–33·5, $H_2O$ 11·5–16); several varieties or species are divided by Tschermak into Orthochlorites and Leptochlorites.[2] When crystallised, they take the form of small green hexagonal tables, but more usually appear in scaly, vermicular or earthy aggregates. They form an essential ingredient of chlorite-schist, and occur abundantly as an alteration product (of hornblende, &c.) in fine filaments, incrustations, and layers in many crystalline rocks. (See under "Chloritisation," Book IV. Part VIII. § ii.) The minerals grouped under the head of Orthochlorites, which present themselves in distinct crystals or in plates of some size, include Clinochlore, Pennine, Ripidolite (prochlorite); the Leptochlorites, usually not definitely crystallised, comprise Cronstedtite, Delessite, Hisingerite, and a large number of variable compounds, which are still imperfectly known.

**Chloritoid.**—Under this general term a group of similar substances is comprised, having a somewhat variable chemical composition but possessing the same or closely similar optical characters. Some of them occur in large plates, others in small scales. Of the latter type perhaps the most important as a rock-constituent is Ottrelite ($H_2O$ (FeMg) $Al_2SiO_7$), which occurs in small lustrous iron-black or greenish-black lozenge-shaped or six-sided plates in certain schists. It resembles chlorite, but is at once distinguishable from that mineral by its much greater hardness.

**Serpentine** (MgO 28–43, FeO 1–10·8, $Al_2O_3$ 0–5·5, $SiO_2$ 37·5–44·5, $H_2O$ 9·5–14·6), long considered to be a distinct mineral, is now recognised as a substance which has resulted from the alteration of various magnesian silicates, more especially of olivine.[3] Under various forms which have received different names, it appears in rents, threads and veins in rocks, into the composition of which these silicates enter. M. Lacroix has divided the serpentine minerals into several distinct types. He classes under the name of Antigorite a mineral which crystallises in pseudocubic forms or in fibro-lamellar masses (Marmolite, Bastite, Baltimorite), and is found in such rocks as the peridotites and those which contain olivine, hornblende, pyroxene, &c. Chrysotile is the name given to the silky finely fibrous forms of serpentine; it includes the varieties Metaxite and Xylotile, and is frequently seen in threads and veins traversing massive serpentine. A mammillated or stalactitic form, distinguished by the concentration in it of the nickel diffused through the original rock, and known as Numeaite, was first recognised in New Caledonia, and has since been detected in the serpentinised lherzolite of the Pyrenees. Bowlingite, a fibro-lamellar mineral found first in the basalt of Bowling on the Clyde, is marked by its considerable percentage of iron; Iddingsite appears to be closely allied to, if not identical with it.

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[1] On Talc and Pyrophyllite deposits, see J. H. Pratt, "Economic Papers," No. 3, *North Carolina Geol. Surv.* 1900.

[2] *Sitzungsb. Akad. Wien.* xcix. (1890), pp. 174-267; F. W. Clarke, *Amer. Journ. Sci.* xl. (1890), p. 405, xlii. (1891), p. 242; *Bull. U. S. G. S.* No. 113 (1893), p. 11.

[3] See Tschermak, *Wien. Akad.* lvi. 1867.

**Glauconite** ($CaO$ 0–4·9, $MgO$ 0–5·9, $K_2O$ 0–12·9, $Na_2O$ 0–2·5, $FeO$ 3–25·5, $Fe_2O_3$ 0–28·1, $Al_2O_3$ 1·5–13·3, $SiO_2$ 46·5–60·09, $H_2O$ 0–14·7). Occurs in small more or less rounded grains which may be agglomerated into layers, strings or longer masses; found only in stratified formations, particularly among sandstones and limestones of marine origin, where it envelops grains of sand, or fills and coats foraminifera and other organisms, giving a general green tint to the rock. It is at present being abundantly formed on the sea-floor.[1] Off the coasts of Georgia and South Carolina, Pourtales found it filling the chambers of recent polythalamia, and since that time it has been met with generally associated with foraminifera or other calcareous organisms in the "green muds" which cover such wide spaces of the ocean-bottom.

CARBONATES.—This family of minerals furnishes only four which enter largely into the formation of rocks, viz. Carbonate of Calcium in its two forms, Calcite and Aragonite, Carbonate of Magnesium (and Calcium) in Dolomite, and Carbonate of Iron in Siderite.

**Calcite** ($CaCO_3$) occurs (1) as an original constituent of many rocks, in almost all cases of sedimentary origin (limestone, calcareous shale, &c.), either formed by chemical deposition from water (calc-sinter, stalactites, &c.), or as a secretion by plants or animals;[2] but in some rare cases, of igneous origin, where the eruptive material has invaded and absorbed limestone and has consequently had calcite crystallised among its silicates;[3] (2) as a secondary product resulting from weathering, when it is found filling or lining cavities, or diffused through the capillary interstices of minerals and rocks. Under the microscope, calcite is readily distinguishable by its intersecting cleavage lines, by a frequent twin lamellation (sometimes giving interference colours), strong double refraction, weak or inappreciable pleochroism, and characteristic iridescent polarisation tints of grey, rose and blue.

From the readiness with which water absorbs carbon-dioxide, from the increased solvent power which it thereby acquires, and from the abundance of calcium in various forms among minerals and rocks, it is natural that calcite should occur abundantly as a pseudomorph replacing other minerals. Thus, it has been observed taking the place of a number of silicates, as orthoclase, oligoclase, garnet, augite and several zeolites; of the sulphates, anhydrite, gypsum, barytes, and celestine; of the carbonates, aragonite, dolomite, cerussite; of the fluoride, fluor-spar; and of the sulphide, galena. Moreover, in many massive crystalline rocks (diorite, dolerite, &c.), which have been long exposed to atmospheric influence, this mineral may be recognised by the brisk effervescence produced by a drop of acid, and in microscopic sections it appears filling the crevices, or sending minute veins among the decayed mineral constituents. Calcite is likewise the great petrifying medium: the vast majority of the animal remains found in the rocky crust of the globe have been replaced by calcite, sometimes with a complete preservation of internal organic structure, sometimes with a total substitution of crystalline material for that structure, the mere outer form of the organism alone surviving. (See Index, *sub voc.* Calcite.)

**Aragonite** ($CaCO_3$), harder, heavier, and much less abundant than Calcite, which is

[1] For a study of Glauconite, as now forming on the sea-floor, see *Report of Challenger*, "Deep Sea Deposits," p. 378; as a constituent of rocks, L. Cayeux, 'Contribution à l'Étude micrographique des Terrains sédimentaires' (1897), chap. iv. See also *postea*, p. 627.

[2] Mr. Sorby has investigated the condition in which the calcareous matter of the harder parts of invertebrates exists. He finds that in foraminifera, echinoderms, brachiopods, crustacea, and some lamellibranchs and gasteropods, it occurs as calcite; that in nautilus, sepia, most gasteropods, many lamellibranchs, &c., it is aragonite; and that in not a few cases the two forms occur together, or that the carbonate of lime is hardened by an admixture of phosphate. *Q. J. G. S.* 1879, Address, p. 61.

[3] Instances of this kind have been described from Scandinavia, Canada, India, and Ceylon. The rock known as elæolite-syenite seems to be specially apt to develop this calcite intermixture when it invades limestones or highly calcareous rocks.

the more stable form of calcium-carbonate : occurs with beds of gypsum, also in mineral veins, in strings running through basalt and other igneous rocks, and in the shells of many mollusca. It is thus always a deposit from water, sometimes from warm mineral springs, sometimes as the result of the internal alteration of rocks, and sometimes through the action of living organisms. Being more easily soluble than calcite, it has no doubt in many cases disappeared from limestones originally formed mainly of aragonite shells, and has been replaced by the more durable calcite, with a consequent destruction of the traces of organic origin. Hence what are now thoroughly crystalline limestones may have been formed by a slow alteration of such shelly deposits (p. 624).

**Dolomite** (Bitter-spar $(Ca,Mg)CO_3$, p. 193) occurs (1) as an original deposit in massive beds (magnesian limestone), belonging to many different geological formations ; (2) as a product of alteration, especially of ordinary limestone or of aragonite (Dolomitisation, pp. 426, 791).[1]

**Siderite** (Brown Ironstone, Spathic Iron, Chalybite, Ferrous Carbonate, $FeCO_3$) occurs crystallised in association with metallic ores, also in beds and veins of many crystalline rocks, particularly with limestones ; the compact argillaceous varieties (clay-ironstone) are found in abundant nodules and beds in the shales of Carboniferous and other formations, where they have been deposited from solution in water in presence of decaying organic matter (see pp. 187, 194).

SULPHATES.—Among the sulphates of the mineral kingdom, only two deserve notice here as important compounds in the constitution of rocks—viz. calcium-sulphate or sulphate of lime in its two forms, Anhydrite and Gypsum ; and barium-sulphate or sulphate of baryta in Barytes.

**Anhydrite** ($CaSO_4$) occurs more especially in association with beds of gypsum and rock-salt (see pp. 189, 194).

**Gypsum** (Selenite, $CaSO_4+2H_2O$). Abundant as an original aqueous deposit in many sedimentary formations (see p. 193).

**Barytes** (Heavy Spar, $BaSO_4$). Frequent in veins, and especially associated with metallic ores as one of their characteristic vein-stones. Occasionally it is found as a cementing material in sandstones.[2]

PHOSPHATES.—The phosphates which occur most conspicuously as constituents or accessory ingredients of rocks are the tricalcic phosphate or Apatite, and triferrous phosphate or Vivianite.

**Apatite** ($3Ca_3(PO_4)+CaF_2$) occurs in many igneous rocks (granites, basalts, &c.), in minute hexagonal non-pleochroic needles, giving faint polarisation tints ; also in large crystals and massive beds associated with metamorphic rocks.[3]

**Vivianite** (Blue iron-earth, $Fe_3P_2O_8$, $8H_2O$) occurs crystallised in metalliferous veins ; the earthy variety is not infrequent in peat-mosses where animal matter has decayed, and is sometimes to be observed coating fossil fishes as a fine layer like the bloom of a plum.

FLUORIDES.—The element fluorine, though widely diffused in nature, occurs as an important constituent of comparatively few minerals. Its most abundant compound is with Calcium as the common mineral Fluorite. It occurs also with sodium and aluminium in the mineral Cryolite (p. 190).

[1] On the distinctive characters of Dolomite in calcareous and dolomitic rocks, see A. Renard, *Bull. Acad. Roy. Belg.* xlvii. (1879), No. 5.

[2] Clowes, *Proc. Roy. Soc.* lxiv. (1899), p. 374 ; C. B. Wedd, *Geol. Mag.* 1899, p. 508 ; W. Mackie, *Brit. Assoc.* 1901, p. 649.

[3] See R. A. F. Penrose on the "Nature and Origin of Deposits of Phosphate of Lime," *B. U. S. G. S.* No. 46 (1888). On the Apatite deposits of Norway, G. Löfstrand, *Geol. Fören. Förhandl.*, Stockholm, xii. (1890), pp. 145-192, 207, 365. On the Apatite of Gellivare, Sweden, H. Lundbohm, *Sverig. Geol. Undersök*, ser. C. No. III. (1890). The subject of phosphate deposits is more fully noticed, *postea*, pp. 180, 626.

**Fluorite** (Fluor-spar, $CaF_2$) occurs generally in veins, especially in association with metallic ores; rarely as the cement of sandstone.[1] For an exhaustive account of Fluorine and its compounds see the monograph by M. Moisson already cited (p. 87).

CHLORIDES.—There is only one chloride of importance as a constituent of rocks—sodium-chloride or common salt (NaCl), which, found chiefly in beds associated with other chemical and mechanical deposits, is described among the rocks at p. 189. Carnallite ($KClMgCl_26H_2O$), a hydrated chloride of potassium and magnesium, occurs in layers together with rock-salt, gypsum, &c., in some salt districts (p. 190).

SULPHIDES.—Sulphur is found united with metals in the form of sulphides, many of which form common minerals. The sulphides of lead, silver, copper, zinc, antimony, &c., are of great commercial importance. Iron-disulphide, however, is the only one which merits consideration here as a rock-forming substance. It is formed at the present day by some thermal springs, and has been developed in many rocks as a result of the action of infiltrating water in presence of decomposing organic matter and iron salts. It occurs in two forms, Pyrite and Marcasite.

**Pyrite** (Eisenkies, Schwefelkies, $FeS_2$) occurs disseminated through almost all kinds of rocks, often in great abundance, as among diabases and clay-slates; also frequent in veins or in beds. In microscopic sections of rocks, pyrite appears in small cubical, perfectly opaque crystals, which with reflected light show the characteristic brassy lustre of the mineral, and cannot thus be mistaken for the isometric magnetite, of which the square sections exhibit a characteristic blue-black colour. Pyrite when free from marcasite yields but slowly to weathering. Hence its cubical crystals may be seen projecting still fresh from slates which have been exposed to the atmosphere for several generations.[2]

**Marcasite** (Hepatic pyrites) occurs abundantly among sedimentary formations, sometimes abundantly diffused in minute particles which impart a blue-grey tint, and speedily weather yellow on exposure and oxidation; sometimes segregated in layers, or replacing the substance of fossil plants or animals; also in veins through crystalline rocks. This form of the sulphide is especially characteristic of stratified fossiliferous rocks, and more particularly of those of Secondary and Tertiary date. It is extremely liable to decomposition. Hence exposure for even a short time to the air causes it to become brown; free sulphuric acid is produced, which attacks the surrounding minerals, sometimes at once forming sulphates, at other times decomposing aluminous silicates and dissolving them in considerable quantity. Dr. Sullivan mentions that the water annually pumped from one mine in Ireland carried up to the surface more than a hundred tons of dissolved silicate of alumina.[3] Iron disulphide is thus an important agent in effecting the internal decomposition of rocks. It also plays a large part as a petrifying medium, replacing the organic matter of plants and animals, and leaving casts of their forms, often with bright metallic lustre. Such casts when exposed to the air decompose.

**Pyrrhotine** (Magnetic pyrites, $Fe_7S_8$) is much less abundant than either of the forms of ordinary iron-pyrites, from which it is distinguished by its inferior hardness and its magnetic character.

It will be observed that great differences exist in the relative abundance of the minerals above enumerated. Thus the igneous rocks, which may be taken to represent the chemical and mineralogical composition of the original part of the earth's crust, are formed out of a small number of

[1] W. Mackie, *Brit. Assoc.* 1901, p. 649.

[2] See J. H. L. Vogt, *Zeitsch. Prakt. Geol.*, Feb., April, May 1894. For an elaborate paper on the decomposition of Pyrites, see A. A. Julien, *Annals New York Acad. Sci.* vols. iii. and iv.

[3] Jukes' 'Manual of Geology,' p. 65.

groups of minerals. Mr. F. W. Clarke, discussing 500 analyses, came to the conclusion that the felspars constitute about 60 per cent of the igneous rocks, the pyroxenes and amphiboles 18 per cent, quartz 12 per cent and micas 4 per cent, making in all 94 per cent, and leaving only 6 per cent for all other groups of minerals.[1] The sedimentary rocks, which either directly or indirectly have been derived from this older or igneous crust, show considerable differences in the relative proportions of their chemical constituents. In the sandstones, for example, the silica percentage sometimes rises above 90, while in the shales it may range between 50 and 60. In the latter rocks the alumina may exceed 15 per cent, while in the sandstones, even in the hard siliceous varieties, used for building purposes, it seldom exceeds from 4 to 6. The alkalies are diminished in the sedimentary formations, but the lime is often much increased, while in the limestones it may form nearly half of the whole rock. These features will come out more clearly when the sedimentary rocks are discussed in Book II. Sect. vii.

## Sect. iii. Determination of Rocks.

Rocks considered as mineral substances are distinguished from each other by certain external characters, such as the size, form, and arrangement of their component particles. These characters, readily perceptible to the naked eye, and in the great majority of cases observable in hand specimens, are termed *megascopic* or *macroscopic* (pp. 109, 127), to distinguish them from the more minute features which, being only visible or satisfactorily observable when greatly magnified, are known as *microscopic* (pp. 119, 140). The larger (geotectonic) aspects of rock-structure, which can only be properly examined in the field, and belong to the general architecture of the earth's crust, are treated of in Book IV.

In the discrimination of rocks, it is not enough to specify their component minerals, for the same minerals may constitute very distinct varieties of rock. For example, quartz and mica form the massive crystalline rock, greisen, the foliated crystalline rock, mica-schist, and the sedimentary rock, micaceous sandstone. Chalk, encrinal limestone, stalagmite, statuary marble are all composed of calcite. It is needful to take note of the megascopic and microscopic structure and texture, the state of aggregation, colour, and other characters of the several masses.

Four methods of procedure are available in the investigation and determination of rocks: 1st, megascopic (macroscopic) examination, either by the rough and ready, but often sufficient, appliances for use in the field, or by those for more careful work indoors; 2nd, chemical analysis; 3rd, chemical synthesis; 4th, microscopic investigation.

### § i. *Megascopic (Macroscopic) Examination.*

**Tests in the field.**—The instruments indispensable for the investigation of rocks in the field are few in number, and simple in character and application. The observer

[1] *B. U. S. G. S.* No. 168 (1900), p. 16.

will be sufficiently accoutred if he carries with him a hammer of such form and weight as will enable him to break off clean, sharp, unweathered chips from the edges of rock-masses, a small lens, a pocket-knife of hard steel for determining the hardness of rocks and minerals, a magnet or a magnetised knife-blade, and a small pocket-phial of dilute hydrochloric acid, or some citric acid in powder.

Should the object be to form a collection of rocks, a hammer of at least three or four pounds in weight should be carried: also one or two chisels and a small trimming hammer, weighing about ½ lb., for reducing the specimens to shape. A convenient size of museum-specimens is $4 \times 3 \times 1$ inches; those of the field geologist will usually be smaller. Where they are meant to be preserved for reference, the specimens should be as nearly as possible uniform in size, so as to be capable of orderly arrangement in the drawers or shelves of a case or cabinet. Attention should be paid not only to obtain a thoroughly fresh fracture of a rock, but also a weathered surface, wherever there is anything characteristic in the weathering. Every specimen should have affixed to it a label, indicating as exactly as possible the locality from which it was taken. This information ought always to be written down in the field at the time of collecting, and should be affixed to or wrapped up with the specimen, before it is consigned to the collecting bag. If, however, the student does not purpose to form a collection, but merely to obtain such chips as will enable him to judge of the characters of rocks, a hammer weighing from 1½ to 2 lbs., with a square face and tapering to a chisel-edge at the opposite end, will be most useful. The advantage of this form is that the hammer can be used not only for breaking hard stones, but also for splitting open shales and other fissile rocks, so that it unites the uses of hammer and chisel.

It is, of course, desirable that the learner should first acquire some knowledge of the nomenclature of rocks, by carefully studying a collection of correctly named and judiciously selected rock-specimens. Such collections may now be purchased at small cost from mineral dealers, or may be studied in the museums of most towns. Having accustomed his eye to the ordinary external characters of rocks, and become familiar with their names, the student may proceed to determine them for himself in the field.

Finding himself face to face with a rock-mass, and after noting its geotectonic characters (Book IV.), the observer will proceed to examine the exposed or weathered surface. The earliest lesson he has to learn, and that of which perhaps he will in after life meet with the most varied illustrations, is the extent to which weathering conceals the true aspect of rocks. From what has been said in previous pages the nature of some of the alterations will be understood, and further information regarding the chemical processes at work will be found in Book III. The practical study of rocks in the field soon discloses the fact, that while, in some cases, the weathered crust so completely obscures the essential character of a rock that its true nature might not be suspected, in other instances it is the weathered crust that best reveals the real composition of the mass. Spheroidal crusts of a decomposing yellow ferruginous earthy substance, for example, would hardly be identified as a compact dark basalt, yet, on penetrating within these crusts, a central core of still undecomposed basalt may not unfrequently be discovered. Again, a block of limestone when broken open may present only a uniformly crystalline structure; yet if the weathered surface be examined it may show many projecting fragments of shells, polyzoa, corals, crinoids, or other organisms. The really fossiliferous nature of an apparently unfossiliferous rock may thus be revealed by weathering. Many limestones also might, from their fresh fracture, be set down as tolerably pure carbonate of lime; but from the thick crust of yellow ochre on their weathered faces are seen to be highly ferruginous. Among crystalline rocks, the weathered surface commonly throws light upon the mineral constitution of the mass, for some minerals decompose more rapidly than others, which are thus left isolated and more easily recognisable. In this manner the existence of quartz in many felspathic rocks may be detected. Its minute blebs or crystals, which to the naked eye or lens

are lost among the brilliant facettes of the felspars, stand out amid the dull clay into which these minerals are decomposed.

The depth to which weathering extends should be noted. The student must not be too confident that he has reached its limit, even when he comes to the solid, more or less hard, splintery, and apparently fresh stone. Granite sometimes decomposes into kaolin and sand to a depth of twenty or thirty feet or more. Limestones, on the other hand, have often a mere film of crust, because their substance is almost entirely dissolved and removed by rain (Book III. Part II. Sect. ii. § 2).

With some practice, the inspection of a weathered surface will frequently suffice to determine the true nature and name of a rock. Should this preliminary examination, and a comparison of weathered and unweathered surfaces, fail to afford the information sought, we proceed to apply some of the simple and useful tests available for field-work. The lens will usually enable us to decide whether the rock is compact and apparently structureless, or crystalline, or fragmental. Having settled this point, we proceed to ascertain the hardness and colour of streak, by scratching a fresh surface of the stone. A drop of acid placed upon the scratched surface or on the powder of the streak may reveal the presence of some carbonate. By practice, considerable facility can be acquired in approximately estimating the specific gravity of rocks merely by the hand. The following table may be of assistance, but it must be understood at the outset that a knowledge of rocks can never be gained from instructions given in books, but must be acquired by actual handling and study of the rocks themselves.

**i. A fresh fracture shows the rock to be close-grained, dull, with no distinct structure.**[1]

α. H. 0·5 or less up to 1; soft, crumbling or easily scratched with the knife, if not with the finger-nail; emits an earthy smell when breathed upon, does not effervesce with acid; is dark grey, brown, or blue, perhaps red, yellow, or even white = probably some clay rock, such as mudstone, massive shale, or fire-clay (p. 168); or a decomposed felspar-rock, like a close-grained felsite or orthoclase porphyry. If the rock is hard and fissile it may be shale or clay-slate (p. 169).

β. H. 1·5–2. Occurs in beds or veins (perhaps fibrous), white, yellow, or reddish. Sp. gr. 2·2–2·4. Does not effervesce = probably gypsum (pp. 107, 193).

γ. Friable, crumbling, soils the fingers, white or yellowish, brisk effervescence = chalk, marl, or some pulverulent form of limestone (pp. 176, 190).

δ. H. 3–4. Sp. gr. 2·5–2·7; pale to dark green or reddish, or with blotched and clouded mixtures of these colours. Streak white; feels soapy; no effervescence, splintery to subconchoidal fracture, edges subtranslucent. See serpentine (p. 241).

ε. H. averaging 3. Sp. gr. 2·6–2·8. White, but more frequently bluish-grey, also yellow, brown, and black; streak white; gives brisk effervescence = some form of limestone (pp. 176, 190).

ζ. H. 3·5–4·5. Sp. gr. 2·8–2·65. Yellowish, white, or pale brown. Powder slowly soluble in acid with feeble effervescence, which becomes brisker when the acid is heated with the powder of the stone. See dolomite (pp. 107, 193).

η. H. 3–4. Sp. gr. 3–3·9. Dark brown to dull black, streak yellow to brown, feebly soluble in acid, which becomes yellow; occurs in nodules or beds, usually with shale; weathers with brown or blood-red crust = brown iron-ore. See clay-ironstone (pp. 107, 187, 194); and limonite (pp. 96, 187, 194); if the rock is reddish and gives a cherry-red streak, see hæmatite (pp. 96, 194).

θ. Sp. gr. 2·55. White, grey, yellowish, or bluish, rings under the hammer, splits

[1] In this table, H. = hardness. The scale of hardness usually employed is 1, Talc; 2, Rock-salt or gypsum; 3, Calcite; 4, Fluorite; 5, Apatite; 6, Orthoclase; 7, Quartz; 8, Topaz; 9, Corundum; 10, Diamond. Sp. gr. = specific gravity; for methods of determining this character, see p. 114.

into thin plates, does not effervesce, weathered crust white and distinct = perhaps some compact variety of phonolite (p. 226. See also felsite, p. 215, and dacite, p. 228).

ι. Sp. gr. 2·9–3·2. Black or dark green, weathered crust yellow or brown = perhaps some close-grained variety of basalt (p. 234), andesite (p. 228), aphanite (p. 224), epidiorite (p. 224), or amphibolite (p. 252).

κ. H. 6–6·5, but less according to decomposition. Sp. gr. 2·55–2·7. Can with difficulty be scratched with the knife when fresh. White, bluish-grey, yellow, lilac, brown, red ; white streak ; sometimes with well-defined white weathered crust, no effervescence = probably a felsitic rock (p. 215).

λ. H. 7. Sp. gr. 2·5–2·9. The knife leaves a metallic streak of steel upon the resisting surface. The rock is white, reddish, yellowish, to brown or black, very finely granular or of a horny texture, gives no reaction with acid = probably silica in the form of jasper, hornstone, flint, chalcedony (pp. 179, 195), hälleflinta (p. 253), or adinole (p. 254).

**ii. A fresh fracture shows the rock to be glassy.**

Leaving out of account some glass-like but crystalline minerals, such as quartz and rock-salt, the number of vitreous rocks is comparatively small. The true nature of the mass in question will probably not be difficult to determine. It may be one of the Massive volcanic rocks (p. 195 *et seq.*). If it occurs in association with siliceous lavas (liparites, trachytes) it will probably be obsidian (p. 213), or pitchstone (p. 216); if it passes into one of the basalt-rocks, as so commonly happens along the edges of dykes and intrusive sheets, it is a glassy form of basalt (p. 235). Each of the three great series of eruptive rocks, Acid, Intermediate, and Basic, has its glassy varieties (see pp. 196, 213, 227, 235).

**iii. A fresh fracture shows the rock to be crystalline.**

If the component crystals are sufficiently large for determination in the field, they may suggest the name of the rock. Where, however, they are too minute for identification even with a good lens, the observer may require to submit the rock to more precise investigation indoors, before its true character can be ascertained. For the purposes of field-work the following points should be noted :—

α. The rock can be easily scratched with the knife.

(*a*) Effervesces briskly with acid = limestone.

(*b*) Powder of streak effervesces in hot acid. See dolomite (pp. 107, 193).

(*c*) No effervescence with acid : may be granular crystalline gypsum (alabaster) or anhydrite (pp. 193, 194).

β. The rock is not easily scratched. It is almost certainly a silicate. Its character should be sought among the massive crystalline rocks (p. 195). If it be heavy, appear to be composed of only one mineral, and have a marked greenish tint, it may be some kind of amphibolite (p. 252) ; if it consist of some white mineral (felspar) and a green mineral which gives it a distinct green colour, while the weathered crust shows more or less distinct effervescence, it may be a fine-grained "greenstone," diorite (p. 224), or diabase (p. 233); if it be grey and granular, with striated felspars and dark crystals (augite and magnetite), with a yellowish or brownish weathered crust, it is probably a dolerite (p. 233) ; if it show a fine grained or finely-crystalline matrix in which porphyritic felspars are enclosed, it may be an andesite (p. 228) ; if it be compact, finely crystalline, scratched with difficulty, showing crystals of orthoclase, and with a bleached argillaceous weathered crust, it may be an orthoclase-porphyry (p. 218), or quartz-porphyry (p. 209). The occurrence of distinct blebs or crystals of quartz in the fresh fracture or weathered face will suggest a place for the rock in the quartziferous crystalline series (granites, quartz-porphyries, rhyolites) ; if the quartz is disposed in long lenticles coated with mica, the rock may belong to the gneisses or schists (pp. 244 *et seq.*).

**iv. A fresh fracture shows the rock to have a foliated structure.**

The foliated rocks are for the most part easily recognisable by the prominence of their component minerals (p. 244). Where the minerals are so intimately mingled as not to be separable by the use of the lens, the following hints may be of service:—

*α*. The rock has an unctuous feel, and is easily scratched. It may be talc-schist, chlorite-schist (p. 253), sericitic mica-schist (p. 255), or foliated serpentine (p. 253).

*β*. The rock emits an earthy smell when breathed on, is harder than those included in *α*, is fine-grained, dark grey in colour, splits with a slaty fracture, and contains perhaps scattered crystals of iron-pyrites or some other mineral. It is some argillaceous-schist or clay-slate, the varieties of which are named from the predominant enclosed mineral, as chiastolite-slate, andalusite-schist, staurolite-slate, ottrelite-schist, &c. (p. 247); if it has a silky lustre it may be a phyllite.

*γ*. The rock is composed of a mass of ray-like or fibrous crystals matted together. If the fibres are exceedingly fine, silky, and easily separable, it is probably asbestos; if they are coarser, greenish to white, glassy, and hard, it is probably an actinolite-schist (p. 252). As above stated (p. 105), many serpentines are seamed with veins of the fine silky fibrous chrysotile, which is easily scratched.

*δ*. The rock has a hardness of nearly 7, and splits with some difficulty along micaceous folia. It is probably a quartzose variety of mica-schist, quartz-schist, or gneiss (pp. 248, 254, 255).

*ε*. The rock shows on its weathered surface lenticles of quartz separated by folia of mica and plates or grains of felspar. It is probably a mica-schist or gneiss.

**v. A fresh fracture shows the rock to have a fragmental (clastic) structure.**

Where the component fragments are large enough to be seen by the naked eye or with a lens, there is usually little difficulty in determining the true nature and proper name of the rock. Two characters require to be specially considered—the component fragments and the cementing paste.

1. The Fragments.—According to the shape, size, and composition of the fragments, different names are assigned to clastic rocks.

*α*. *Shape.*—If the fragments are chiefly rounded, the rock may be sought in the sand and gravel series (p. 160); while if they are large and angular, it may be classed as a breccia (p. 163). Some mineral substances do not acquire rounded outlines, even after long-continued attrition. Mica, for example, splits up into thin laminæ, which may be broken into small flakes or spangles, but never become rounded granules. Other minerals, also, which have a ready cleavage, are apt to break up along their cleavage-planes, and thus to retain angular contours. Calc-spar is a familiar example of this tendency. Organic remains composed of this mineral (such as crinoids and echinoids) may often be noticed in a very fragmentary condition, having evidently been subjected to long-continued comminution. Yet angular outlines and fresh or little-worn cleavage-surfaces may be found among them. Many limestones consist largely of sub-angular organic débris. Angular inorganic detritus is characteristic of volcanic breccias and tuffs (p. 172).

*β*. *Size.*—Where the fragments are hard, rounded, or sub-angular quartzose grains, the size of a pin's-head or less, the rock is probably some form of sandstone (p. 164). Where they range up to the size of a pea, it may be a pebbly sandstone, fine conglomerate or grit; where they vary from the size of a pea to that of a walnut, it is an ordinary gravel or conglomerate; where they range up to the size of a man's head or larger, it is a coarse shingle, conglomerate, or boulder-bed. A considerable admixture of sub-angular stones makes it a brecciated conglomerate or breccia; but where the materials are loosely aggregated, the deposit may be scree-material (p. 160) or some

kind of glacial drift, such as moraine-stuff or boulder-clay (p. 169). Large angular and irregular blocks are characteristic of coarse volcanic agglomerates (p. 173).

$\gamma$. *Composition.*—In the majority of cases, the fragments are of quartz, or at least of some siliceous and enduring mineral. Sandstones consist chiefly of rounded quartz-grains (p. 164). Where these are unmixed with other ingredients, the rock is sometimes distinguished as a quartzose sandstone. Such a rock when indurated becomes quartzite (p. 249). Among the quartz-grains, minute fragments of other minerals may be observed. When any one of these is prominent, it may give a name to the variety of sandstone or of greywacke (pp. 164, 166). Volcanic tuffs and breccias are characterised by the occurrence of lapilli (very commonly *cellular*) of the lavas from the explosion of which they have been formed. Among interbedded volcanic rocks, the student will meet with some which he may be at a loss whether to class as volcanic, or as formed of ordinary sediment. They consist of an intermixture of volcanic detritus with sand or mud, and pass on the one side into true tuffs, on the other into sandstones, shales, limestones, &c. If the component fragments of a non-crystalline rock give a brisk effervescence with acid, they are calcareous, and the rock (most likely a limestone, or at least of calcareous composition) may be searched for traces of fossils.

2. The Paste.—It sometimes happens that the component fragments of a clastic rock cohere merely from pressure and without any discoverable matrix. This is occasionally the case with sandstone. Most commonly, however, there is some cementing paste. If a drop of weak acid produces effervescence from between the component non-calcareous grains of a rock, the paste is calcareous. It the grains are coated with a red crust which, on being bruised between white paper, gives a cherry-red powder, the cementing material is the anhydrous peroxide of iron. If the paste is yellow or brown it is probably in great part the hydrous peroxide of iron. A dark brown or black matrix which can be dissipated by heating is bituminous. Where the component grains are so firmly cemented in an exceedingly hard matrix that they break across rather than separate from each other when the stone is fractured, the paste is probably siliceous, as in quartzite.

**Determination of Specific Gravity.**—The student will find this character of considerable advantage in enabling him to discriminate between rocks. He may acquire some dexterity in estimating, even with the hand, the probable specific gravity of substances; but he should begin by determining it with a balance. Jolly's spring balance is a simple and serviceable instrument for this purpose. It consists of an upright stem having a graduated strip of mirror let into it, in front of which hangs a long spiral wire, with rests at the bottom for weighing a substance in air and in water. For most purposes it is sufficiently accurate, and a determination can be made with it in the course of a few minutes.[1] Another and more convenient instrument has been invented by W. N. Walker. consisting of a lever graduated into inches and tenths, and resting on a knife-edge stand, on one side of which is placed a movable weight, while on the long graduated side the substance to be weighed is suspended. This instrument has the advantage of not being so liable to get out of order as other contrivances.[2] A third instrument, made by G. Westphal of Cella, Hanover, also on the beam principal, affords the means of making delicate and accurate determinations.

**Mechanical Analysis.**—Much may be learnt regarding the composition of a rock by reducing it to powder. In the case of many sandstones and clays this reduction may easily be effected by drying the stone and crumbling it between the fingers. But where

[1] Jolly's spring balance can be obtained through any optician or mineral dealer from Berberich, of Munich, for nine florins or 27*s*. In the United States it is manufactured by Geo. Wadé and Co., at the Hoboken Institute.

[2] See *Geol. Mag.* 1883, p. 109, for a description and drawing of this instrument, and the manner of using it. It may be obtained of Lowden, optician, Dundee, and How and Co., Farringdon Street, London. Its price is 31*s*. 6*d*.

the material is too compact for such treatment, some fragments of it, placed within folds of paper upon a surface of steel, may be reduced to powder by a few smart blows of a hammer, care being taken not to grind the particles into mere dust. The powder can be sifted through sieves of varying degrees of fineness and the separate fragments may be picked out with a fine brush and examined with a lens. If they are dark in colour they may be placed on white paper; if light-coloured they are more readily observed upon a black paper. Portions of this powder may be carefully washed and mounted with Canada balsam on glass, as in the way described below for microscopic slices. In this way the constituent minerals of many crystalline rocks may be isolated and studied with great facility. For purposes of comparison specimens of the rock-forming minerals should be procured and treated in a similar way. A series of typical preparations of the powder or minute fragments of such minerals affords to the student an admirable basis from which to start in his study of the crystallographic and optical characters of the minerals which he will require to identify among the constituents of rocks. It is deserving of notice that this method of investigating the composition of rocks was first put in practice by Cordier early in the nineteenth century. He crushed well-known minerals to powder and studied the characters of their minute fragments with a microscope. Proceeding next to rocks, he was able to identify the minerals composing many of them and to separate them out from the surrounding matrix.[1]

Another method of isolating the several components of certain rocks is by washing the triturated materials in water and allowing the sediment to subside. The finer and lighter particles may be drawn off, while the coarser and heavier grains will sink according to their respective specific gravities, and may then be separated and collected. This may be done by means of a wide tube with a stop-cock at the bottom, or by gently washing the powder with water on an inclined surface, when, as in the analogous treatment of vein-stones and ores in mining, the particles arrange themselves according to their respective gravities, the lightest being swept away by the current.

Magnetic particles may be extracted with a magnet, the end of which is preserved from contact with the powder by being covered with fine tissue-paper. An electro-magnet will at once withdraw the particles of minerals which contain far too little iron to be ordinarily recognised as magnetic; in this way the particles of a ferruginous magnesian mica may in a few seconds be gathered out of the powder of a granite.[2]

Where the difference between the specific gravity of the component minerals of a rock is slight, they may be separated by means of a solution of given density. Mr. E. Sonstadt proposed the use of a saturated solution of iodide of mercury in iodide of potassium, which has a maximum density of nearly 3·2.[3] Rohrbach's solution, consisting of iodide of mercury and iodide of barium, has a density of as much as 3·588.[4] More serviceable is the solution of borotungstate of cadmium, with a density of 3·28, proposed by D. Klein.[5] The powder of a rock being introduced into one of these liquids, those particles whose specific gravity exceeds that of the liquid will sink to the bottom, while those which are lighter will float. This process allows of the separation of the felspars from each other, and at once eliminates the heavy minerals such as hornblende, augite and black mica. By the addition of water or other liquid, as the case may be,

[1] The work of this eminent pioneer will be found in the *Journ. de Phys.* lxxxiii. (1816), pp. 135, 285, 352.

[2] *Mém. Acad. des Sci.* xxxii. No. 11; Fouqué and Michel-Lévy, 'Minéralogie Micrographique,' p. 115.

[3] *Chem. News*, xxix. (1874), p. 128.

[4] *Neues Jahrb.* 1883, p. 186.

[5] *Compt. rend.* xciii. (1881), p. 318. R. Brauns introduced methylene iodide, which gives a density of 3·33 and is diluted with benzole. *Neues Jahrb.* 1886, ii. p. 72. See also J. W. Retgers, *op. cit.* 1889, ii. p. 185. A heavy liquid, obtained by mixing nitrates of silver and thallium in equal proportions, is preferred by some petrographers.

the specific gravity may be reduced, and different solutions of given density may be employed for determining and isolating rock-constituents.[1]

Professor Sollas has devised an ingenious but simple method of separating and ascertaining the specific gravity of the mineral components of a rock.[2] A fragment of the rock to be examined, about the size of a hazel-nut, is crushed to powder in the usual way, sifted, washed and dried. A diffusion column is formed by half-filling a glass tube with one of the heavy solutions, adding water above, and allowing it to stand for some hours until the column of liquid increases uniformly in density from the top to the bottom. Little indexes are then dropped into the column, which may be fragments of minerals or of chemically pure substances of known density, or portions of capillary glass-tubes enclosing a little mercury, the chief point being that the density of each of them has been accurately ascertained. Each index will float in that portion of the column which agrees with it in density. The column may thus be divided by a series of these indexes; and the minerals of the rock, suspended each in the layer of its own density, have thus their respective specific gravities clearly indicated.

Hydrofluoric acid may be used in separating the mineral constituents of rocks. The rock to be studied is reduced to powder and introduced gently into a platinum capsule containing the concentrated acid. During the consequent effervescence, the mixture is cautiously stirred with a platinum spatula. Some minerals are converted into fluorides, others into fluosilicates, while some, particularly the iron-magnesia species, remain undissolved. The thick jelly of silica and alumina is removed with water, and the crystalline minerals lying at the bottom can then be dried and examined. By arresting the solution at different stages the different minerals may be isolated. This process is admirably adapted for collecting the pyroxene of pyroxenic rocks.[3]

### § ii. *Chemical Analysis.*[4]

The determination of the chemical composition of rocks by detailed analysis in the wet way, demands an acquaintance with practical chemistry which comparatively few geologists possess, and is consequently relegated to specially trained chemists, whose researches are most fruitful when they have grasped the nature of the problems on which these researches may throw light. Unfortunately the older analyses are markedly incomplete, and for many purposes of little value, owing partly to defective methods and partly to the want of recognition of the importance of determining the presence and proportions of many ingredients which, though occurring in minute quantities, have much importance in many theoretical questions. Among the components of rocks not separately estimated in these analyses when present in small amounts were titanic acid, manganese, chromic oxide, strontia, baryta, lithia, phosphoric acid, sulphuric acid, fluorine, and chlorine. More detailed examinations are now conducted, and the modern analyses contrast favourably with those made less than a generation ago.[5]

[1] Fouqué and Michel-Lévy, 'Minéralogie Micrographique,' p. 177. Thoulet, *Bull. Soc. Min. France*, ii. (1879), p. 17. An ingenious apparatus for isolating minerals by means of heavy solutions was designed by Mr. W. F. Smeeth, *Sci. Proc. Roy. Dublin. Soc.* vi. (1888), p. 58. A cheap form of instrument for the same purpose is described by Mr. J. W. Evans, *Geol. Mag.* 1891, p. 67. See also S. L. Penfield, *Amer. Journ. Sci.* (1895), p. 446.

[2] *Nature*, xliii. (1891), p. 404; xlix. (1893), p. 211; liii. (1895), p. 199; *Trans. Roy. Irish Acad.* xxix. (1891), p. 429.

[3] Fouqué and Michel-Lévy, 'Minéral. Microg.' p. 116.

[4] The great pioneer work on the chemistry of rocks was that of G. Bischof, 'Chemical Geology,' translated for the Cavendish Society, 1854-59, and Supplement, Bonn, 1871. Another valuable work is Roth's 'Allgemeine und Chemische Geologie,' Berlin, 1879. Some of the best modern work in chemical geology will be found in the Bulletins and other publications of the United States Geological Survey. Further references to authorities on this subject are given in the following pages.

[5] Much credit for its share in this reform is due to the Geological Survey of the United

For the adequate discussion of some theoretical questions in geology a considerable acquaintance with modern chemistry is necessary. Although, as a rule, detailed chemical analysis lies out of the sphere of a geologist's work, yet the wider his knowledge of chemical laws and methods the better. He should at least be able to employ with accuracy the simpler processes of chemical research.

*Treatment with Acid.*—The geologist's accoutrements for the field should include a small bottle of powdered citric acid, or one with a mineral acid, and provided with a glass stopper prolonged downwards into a point. Dilute hydrochloric acid has been commonly employed; but H. C. Bolton proposed in 1877 the use of organic acids in place of the usual mineral acids. Citric acid is particularly serviceable for the purpose, and has the advantage over the mineral acids that it can be carried in powder, and a strong solution of it in water can be made in such quantity and at such time as may be required. A little of the powder placed with the point of a knife on a surface of limestone and moistened with a drop of water will give the proper reaction.[1]

When a drop of acid gives effervescence upon a surface of rock, the reaction is caused by the liberation of bubbles of carbon dioxide, as this oxide is replaced by the more powerful acid. Hence effervescence is an indication of the presence of carbonates, and when brisk is specially characteristic of calcium-carbonate. Limestone and markedly calcareous rocks may thus at once be detected. By the same means, the decomposition of such rocks as dolerite may be traced to a considerable distance inward from the surface, the original lime-bearing silicate of the rock having been decomposed by infiltrating rain-water, and partially converted into carbonate of lime. This carbonate being more sensitive to the acid-test than the other carbonates usually to be met with among rocks, a drop of weak cold acid suffices to produce abundant effervescence even from a crystalline face. But the effervescence becomes much more marked if we apply the acid to the powder of the stone. For this purpose, a scratch may be made and then touched with acid, when a more or less copious discharge of carbonic acid may be obtained, where otherwise it might appear so feebly as perhaps even to escape observation. Some carbonates, dolomite for example, are hardly affected by acid until it is heated. This is done by placing some fragments of the substance at the bottom of a test-tube, covering them with acid and applying a flame.

It is a convenient method of roughly estimating the purity of a limestone, to place a fragment of the rock in acid. If there is much impurity (clay, sand, oxide of iron, &c.), this will remain behind as an insoluble residue, and may then be further tested chemically, or examined with the microscope. In this way many limestones among the crystalline schists may be dissolved in acetic acid, leaving a residue of pyroxenes, amphiboles, micas or other silicates. Of course the acid, especially if strong mineral acid is employed, may attack some of the non-calcareous constituents, so that it cannot be concluded that the residue absolutely represents everything present in the rock except the carbonate of lime; but the proportion of non-calcareous matter so dissolved by the acid will usually be small.

*Further chemical processes.*—A thorough chemical analysis of a rock or mineral is indispensable for the elucidation of its composition. But there are several processes by

States and the very able chemists of its laboratory, Mr. F. W. Clarke, Dr. W. F. Hillebrand, and their assistants. They published an excellent account of their analytical methods in 1897 (*B. U. S. G. S.* No. 148), which has since been enlarged into a separate memoir with the title, "Some Principles and Methods of Rock Analysis," by W. F. Hillebrand (*B. U. S. G. S.* No. 176, 1900, p. 114. The student who desires to undertake the detailed chemical examination of rocks will find this an invaluable treatise for his guidance. The greater detail and accuracy of the American analyses justifies a much larger citation of them than has hitherto been given.

[1] *Ann. New York Acad. Sci.* i. (1879), p. 1. *Chem. News*, xxxvi., xxxvii., xxxviii., xliii.

which, until that complete analysis has been made, the geologist may add to his knowledge of the chemical nature of the objects of his study. It is commonly the case that minerals about which he may be doubtful are precisely those which, from their small size, are most difficult of separation from the rest of the rock preparatory to analytical processes. The mineral apatite, for example, occurs in minute hexagonal prisms, which on cross-fracture might be mistaken for nepheline, or even sometimes for quartz. If, however, a drop of nitric acid solution of molybdate of ammonia be placed upon one of these crystals, a yellow precipitate will appear if it be apatite. Nepheline, which is another hexagonal mineral likewise abundant in some rocks, gives no yellow precipitate with the ammonia solution; while if a drop of hydrochloric acid be put over it, crystals of chloride of sodium or common salt will be obtained. These reactions can be observed even with minute crystals or fragments, by placing them on a glass slide under the microscope and using an exceedingly attenuated pipette for dropping the liquid on the slide.[1]

Two ingenious applications of chemical processes to the determination of minute fragments of minerals are now in use. In one of these, devised by Boricky,[2] hydrofluosilicic acid of extreme purity is employed. This acid decomposes most silicates, and forms from their bases hydrofluosilicates. A particle about the size of a pin's-head of the mineral to be examined is fixed by its base upon a thin layer of Canada balsam spread upon a slip of glass, and a drop of the acid is placed upon it. The preparation is then set in moist air near a saucer of water under a bell-glass for twenty-four hours, after which it is enclosed in dry air, with chloride of calcium. In a few hours the hydrofluosilicates crystallise out upon the balsam and can be examined with the microscope. Those of potassium take the form of cubes, of sodium hexagonal prisms, &c.

The second process, devised by Szabo, consists in utilising the colorations given to the flame of a bunsen-burner by sodium and potassium. An elongated splinter of the mineral to be examined is first placed in the outer or oxidising part of the flame near the base, and then in the reducing part further up and nearer the centre. The amount of sodium present in the mineral is indicated by the extent to which the flame is coloured yellow. The potassium is similarly estimated, but the flame is then looked at with cobalt glass, so as to eliminate the influence of the sodium.[3]

*Blow-pipe Tests.*—The chemical tests with the blow-pipe are simple, easily applied, and require only patience and practice to give great assistance in the determination of minerals. If unacquainted with blow-pipe analysis, the student must refer to one or other of the numerous text-books on the subject, some of which are mentioned below.[4]

[1] An excellent treatise on the chemical examination of minerals under the microscope is that by MM. Klement and Renard, 'Réactions microchemiques à cristaux et leur application en analyse qualitative,' Brussels, 1886. See also H. Behrens, *Ann. École Polytechnique de Delft*, i. 1885, p. 176; *Neues Jahrb.* vii. Beilage Band, p. 435; *Zeitsch. f. Analyt. Chemie*, xxx. ii. p. 126-174 (1891); also his 'Manual of Microchemical Analysis,' translated into English, London, 1894; and the work of MM. Michel-Lévy and Lacroix (cited on next page), chap. viii.

[2] *Archiv Naturwiss. Landesdurchforschung von Böhmen*, iii. fasc. 3, 1876; 'Elemente einer neuen chemisch-mikroskopischen Mineral- und Gesteinsanalyse,' Prag, 1877. Also Michel-Lévy and Lacroix, p. 123.

[3] Szabo, 'Ueber eine neue Methode die Felspathe auch in Gesteinen zu bestimmen,' Buda-Pest, 1876.

[4] The great work on the blow-pipe is Plattner's, of which an English translation has been published by Chatto and Windus. Elderhorst's 'Manual of Qualitative Blow-pipe Analysis and Determinative Mineralogy,' by H. B. Nason and C. F. Chandler (Philadelphia: N. S. Porter and Coates), is a smaller but useful volume; while still less pretending are Scheerer's 'Introduction to the Use of the Mouth Blow-pipe,' of which a third edition by H. F. Blandford

For early practice the following apparatus will be found sufficient :—

1. Blow-pipe.
2. Thick-wicked candle, or a tin box filled with the material of Child's night-lights, and furnished with a piece of Freyberg wick in a metallic support.
3. Platinum-tipped forceps.
4. A few pieces of platinum wire in lengths of three or four inches.
5. A few pieces of platinum foil.
6. Some pieces of charcoal.
7. A number of closed and open tubes of hard glass.
8. Three small stoppered bottles containing sodium-carbonate, borax, and microcosmic salt.
9. Magnet.

This list can be increased as experience is gained. The whole apparatus may easily be packed into a box which will go into the corner of a portmanteau.

## § iii. *Chemical Synthesis.*

As already remarked (p. 88), much interesting light has been thrown on the natural conditions in which minerals and rocks have been formed, by actual experiments in which these bodies are reproduced artificially. Since the classic experiments of Hall much progress has been made in this subject, notably from the researches of the late Professor Daubrée and of Messrs. Fouqué and Michel-Lévy, Doelter and Hussak, Morozewicz, Vogt and others. To some of the results obtained by these observers reference will be made in Book III. Part I. Sect. iv. The processes of investigation have been grouped in three classes:—1st, Those by the 'dry way,' as in fusion and sublimation, sometimes simply, sometimes with the intervention of a mineralising agent such as borax, borates, fluorides, chlorides, &c; 2nd, Those by the 'wet way,' where water or steam, at ordinary pressures and temperatures, are used as dissolvents either by themselves or with the aid of some mineralising agent; and 3rd, Those where some combination of the two foregoing methods is employed—that is, where water or steam is made to act at a high temperature and under great pressure.[1]

## § iv. *Microscopic Investigation.*[2]

The value of the microscope as an aid in geological research is now everywhere acknowledged. Some information may here be given as to the methods of procedure in microscopical inquiry. The method of cutting thin slices of minerals was devised by

was published in 1875 by F. Norgate; and 'Practical Blow-pipe Assaying,' by G. Attwood (London: Sampson, Low and Co.). An admirable work of reference will be found in Professor Brush's 'Manual of Determinative Mineralogy' (New York: J. Wiley and Son; London: Trübner), which has gone through fourteen editions. F. v. Kobell's 'Tafeln zur Bestimmung der Mineralien' (Munich) are useful; a French edition by Pisani was published by Rothschild, Paris, 1879. A valuable summary is given in Professor Cole's 'Aids in Practical Geology,' 3rd edit. 1898.

[1] See on this subject Daubrée's great work, 'Géologie Expérimentale,' 1879; Fouqué and Michel-Lévy, 'Synthèse des Minéraux et des Roches,' 1882; Stanislas Meunier, 'Les Méthodes de Synthèse en Minéralogie,' 1891; also *postea*, p. 398 *et seq.*

[2] The microscopic investigation of rocks has given rise to a somewhat voluminous literature. The following list of works may be useful to the student:—Zirkel, 'Lehrbuch der Petrographie,' 2nd edit. 3 vols. Leipzig, 1893-94. Rosenbusch, 'Mikroskopische Physiographie der Mineralien und Gesteine,' 2 vols. 3rd edit. Stuttgart, 1896; also the English translation, 'Microscopical Physiography of the Rock-forming Minerals,' by J. P. Iddings, 3rd edit. 1893, New York and London; and his 'Hülfstabellen zur Mikroskopischen Mineralbestimmung,' 1888; English translation by F. H. Hatch. Fouqué and Michel-Lévy, 'Minéralogie Micrographique,' 2 vols. Paris, 1879. Michel-Lévy and Lacroix, 'Les Minéraux

William Nicol of Edinburgh, the same ingenious mechanician to whom we owe the prism of Iceland spar named after him. He applied it in the first instance to the examination of fossil wood.[1] More than a quarter of a century elapsed before Mr. Sorby, coming to Edinburgh and seeing some of the sections of minerals prepared by Nicol and his friend Alexander Bryson, recognised the vast assistance which this method of investigating rocks might be made to yield to geology. At last he published his great paper "On the Microscopical Structure of Crystals," in which the applications of the method were for the first time disclosed, and which may be said to have entirely revolutionised the study of rocks.[2]

1. **Preparation of Microscopic Slides of Rocks and Minerals.**—The observer ought to be able to prepare his own slices, and in many cases will find it of advantage to do so, or at least personally to superintend their preparation by others. It is desirable that he should know at the outset that no costly or unwieldy set of apparatus is needful for his purpose. If he is resident in one place and can accommodate a cutting machine, such as a lapidary's lathe, he will find the process of preparing rock-slices greatly facilitated.[3] The thickness of each slice must be mainly regulated by the nature of the rock, the rule being to make the slice as thin as can conveniently be cut, so as to save labour in grinding down afterwards. Perhaps the thickness of a shilling may be taken as a fair average. The operator, however, may still further reduce this thickness by cutting and polishing a face of the specimen, cementing that on glass in the way to be immediately described, and then cutting as close as possible to the cemented surface. The thin slice thus left on the glass can then be ground down with comparative ease.

des Roches,' 1888; 'Tableau des Minéraux des Roches,' 1889. F. Rutley, 'Study of Rocks,' London, 1879; 'Rock-forming Minerals,' 1888. J. J. H. Teall, 'British Petrography,' London, 1888. A. Harker, 'Petrology for Students,' 2nd edit. Cambridge, 1897. Cole's 'Aids in Practical Geology,' above referred to. L. Cayeux, 'Contribution à l'Étude micrographique des Terrains sédimentaires,' Lille, 1897. Besides these and many other separate works, hundreds of memoirs and papers dealing with particular districts or rocks will be found in the various scientific journals, Transactions of Societies, Reports and Monographs of Geological Surveys. Some of the more important or suggestive of these essays will be cited in the following pages. A valuable series of photographic reproductions of the structure of typical rocks has been prepared by Cohen, 'Sammlung von Microphotografien von Mineralien und Gesteine,' Stuttgart, 1881 *et seq.*; chromolithographed plates have been published by Berwerth, 'Mikroskopische Strukturbilder der Massengesteine,' Stuttgart, 1895 *et seq.*

[1] Witham's 'Fossil Vegetables,' small 4to, Edinburgh, 1831. This work, dedicated to Nicol, contains the first published account by him of his invention.

[2] *Brit. Assoc.* 1856, Sect. p. 78. *Q. J. G. S.* xiv. 1858; *Micr. Journ.* xvii. (1887), p. 113.

[3] A machine well adapted for both cutting and polishing was devised some years ago by Mr. J. B. Jordan, and may be had of Messrs. Cotton and Johnson, Gerrard Street, Soho, London, for £10 : 10*s*. Another slicing and polishing machine, invented by Mr. F. Cuttell, costs £6 : 10*s*. These machines are too unwieldy to be carried about the country by a field-geologist. Fuess of Berlin supplies two small and convenient hand-instruments, one for slicing, the other for grinding and polishing. The slicing-machine is not quite so satisfactory for hard rocks as one of the larger, more solid forms of apparatus worked by the treadle. But the grinding-machine is useful, and might be added to a geologist's outfit without material inconvenience. If a lapidary is within reach, much of the more irksome part of the work may be saved by getting him to cut off the thin slices in directions marked for him upon the specimens. Many lapidaries now undertake the whole labour of cutting and mounting microscopic slides; and where exceedingly thin and even slices are required, it is better to entrust the work to one of the best of these experts, who have mechanical appliances and experience such as the amateur cannot rival.

Excellent rock-sections, however, may be prepared without any machine, provided the operator possesses ordinary neatness of hand and patience. He must procure as thin chips as possible. Should the rocks be accessible to him in the field, he should select the freshest portions of them, and by a dexterous use of the hammer break off from a sharp edge a number of thin splinters or chips, out of which he can choose one or more for rock-slices. These chips may be about an inch square. It is well to take several of them, as the first specimen may chance to be spoiled in the preparation. The geologist ought also always to carry off a piece of the same block from which his chip is taken, that he may have a specimen of the rock for future reference and comparison. Every such hand-specimen, as well as the chips belonging to it, ought to be wrapped up in paper on the spot where it is obtained, and with it should be placed a label containing the name of the locality and any notes that may be thought necessary. It can hardly be too frequently reiterated that all such field-notes ought as far as possible to be written down on the ground, when the actual facts are before the eye for examination.

Having obtained his thin slices, either by having them slit with a machine or by detaching with a hammer as thin splinters as possible, the operator may proceed to the preparation of them for the microscope. For this purpose the following simple apparatus is all that is absolutely needful, though if a grinding-machine be added it will save time and labour.

*List of Apparatus required in the Preparation of Thin Slices of Rocks and Minerals for Microscopical Examination.*

1. A cast-iron plate ½-inch thick and 9 inches square.
2. Two pieces of plate-glass, 9 inches square.
3. A Water of Ayr stone, 6 inches long by 2½ inches broad.
4. Coarse emery (1 lb. or so at a time).
5. Fine or flour-emery (ditto).
6. Putty powder (1 oz.).
7. Canada balsam. (There is an excellent kind prepared by Rimmington, Bradford, specially for microscopic preparations, and sold in shilling bottles.)
8. A small forceps, and a common sewing-needle with its head fixed in a cork.
9. Some oblong pieces of common flat window-glass ; 2 × 1 inches is a convenient size.
10. Glasses with ground edges for mounting the slices upon. They may be had at any chemical-instrument maker's in different sizes, the commonest in this country being 3 × 1 inches, though this size is rather too long for convenient handling on a rotating stage.
11. Thin covering-glasses, square or round. These are sold by the ounce ; ¼ oz. will be sufficient to begin with.
12. A small bottle of spirits of wine.

The first part of the process consists in rubbing down and polishing one side of the chip or slice, if this has not already been done in cutting off a slice affixed to glass, as above mentioned. We place the chip upon the wheel of the grinding-machine, or, failing that, upon the iron plate, with a little coarse emery and water. If the chip is so shaped that it can be conveniently pressed by the finger against the plate and kept there in regular horizontal movement, we may proceed at once to rub it down. If, however, we find a difficulty, from its small size or otherwise, in holding the chip, one side of it may be fastened to the end of a bobbin or other convenient bit of wood by means of a cement formed of three parts of resin and one of beeswax, which is easily softened by heating. A little practice will show that a slow, equable motion with a certain steady pressure is most effectual in producing the desired flatness of surface. When all the roughnesses have been removed, which can be told after the chip has been dipped in water so as to remove the mud and emery, we place the specimen upon the

square of plate-glass, and with flour-emery and water continue to rub it down until all the scratches caused by the coarse emery have been removed and a smooth polished surface has been produced.[1] Care should be taken to wash the chip entirely free of any grains of coarse emery before the polishing on glass is begun. It is desirable also to reserve the glass for polishing only. The emery gets finer and finer the longer it is used, so that by remaining on the plate it may be used many times in succession. Of course the glass itself is worn down; but by using alternately every portion of its surface and on both sides, one plate may be made to last a considerable time. If after drying and examining it carefully, we find the surface of the chip to be polished and free from scratches, we may advance to the next part of the process. But it will often happen that the surface is still finely scratched. In this case we may place the chip upon the Water of Ayr stone and with a little water gently rub it to and fro. It should be held quite flat. The Water of Ayr stone, too, should not be allowed to get worn into a hollow, but should also be kept quite flat, otherwise we shall lose part of the chip. Some soft rocks, however, will not take an unscratched surface even with the Water of Ayr stone. These may be finished with putty powder, applied with a bit of woollen rag.

The desired flatness and polish having been secured, and all trace of scratches and dirt having been completely removed, we proceed to a further stage, which consists in grinding down the opposite side and reducing the chip to the requisite degree of thinness. The first step is now to cement the polished surface of the chip to one of the pieces of common glass. A thin piece of iron (a common shovel does quite well) is heated over a fire, or is placed between two supports over a gas-flame.[2] On this plate must be laid the piece of glass to which the slice is to be affixed, together with the slice itself. A little Canada balsam is dropped on the centre of the glass and allowed to remain until it has acquired the necessary consistency. To test this condition, the point of a knife should be inserted into the balsam, and on being removed should be rapidly cooled by being pressed against some cold surface. If it soon becomes hard enough to resist the pressure of the finger-nail, it has been sufficiently heated. Care, however, must be observed not to let it remain too long on the hot plate; for it will then become brittle and start from the glass at some future stage, or at least will break away from the edges of the chip and leave them exposed to the risk of being frayed off. The heat should be kept as moderate as possible, for if it becomes too great it may injure some portions of the rock. Chlorite, for example, is rendered quite opaque if the heat is so great as to drive off its water.

When the balsam is found to be ready, the chip, which has been warmed on the same plate, is lifted with the forceps, and laid gently down upon the balsam. It is well to let one end touch the balsam first, and then gradually to lower the other, as in this way the air is driven out. With the point of a needle or a knife the chip should be moved about a little, so as to expel any bubbles of air and promote a firm cohesion between the glass and the stone. The glass is now removed with the forceps from the plate and put upon the table, and a lead weight or other small heavy object is placed upon the chip, so as to keep it pressed down until the balsam has cooled and hardened. If the operation has been successful, the slide ought to be ready for further treatment as soon as the balsam has become cold. If, however, the balsam is still soft, the glass must be again placed on the plate and gently heated, until, on cooling, the balsam fulfils the condition of resisting the pressure of the finger-nail.

[1] Exceedingly impalpable emery powder may be obtained by stirring some of the finest emery in water, and after the coarse particles have subsided, pouring off the liquid and allowing the fine suspended dust gradually to subside. Filtered and dried, the residue can be kept for the more delicate parts of the polishing.

[2] A piece of wire-gauze placed over the flame, with an interval of an inch or more between it and the overlying thin iron plate, by diffusing the heat prevents the balsam from being unequally heated.

Having now produced a firm union of the chip and the glass, we proceed to rub down the remaining side of the stone with coarse emery on the iron plate as before. If the glass cannot be held in the hand or moved by the simple pressure of the fingers, which usually suffices, it may be fastened to the end of the bobbin with the cement as before. When the chip has been reduced until it is tolerably thin—until, for example, light appears through it when held between the eye and the window,—we may, as before, wash it clear of the coarse emery and continue the reduction of it on the glass plate with fine emery. Crystalline rocks, such as granite, gneiss, diorite, dolerite, and modern lavas, can be thus reduced to the required thinness on the glass plate. Softer rocks may require gentle treatment with the Water of Ayr stone.

The last parts of the process are the most delicate of all. We desire to make the section as thin as possible, and for that purpose continue rubbing until after one final attempt we may perhaps find to our dismay that great part of the slice has disappeared. The utmost caution should be used. The slide should be kept as flat as possible, and looked at frequently, that the first indications of disruption may be detected. The thinness desirable or attainable depends in great measure upon the nature of the rock. Transparent minerals need not be so much reduced as more opaque ones. Some minerals, indeed, remain absolutely opaque to the last, like pyrite, magnetite, and ilmenite.

The slide is now ready for the microscope. It ought always to be examined with that instrument at this stage. We can thus see whether it is thin enough, and if any chemical tests are required they can readily be applied to the exposed surface of the slice. If the rock has proved to be very brittle, and we have only succeeded in procuring a thin slice after much labour and several failures, nothing further should be done with the preparation, unless to cover it with glass, as will be immediately explained, which not only protects it, but adds to its transparency. But where the slice is not so fragile, and will bear removal from its original rough scratched piece of glass, it should be transferred to one of the glass-slides (No. 10). For this purpose, the preparation is once more placed on the warm iron plate, and close alongside of it is put one of the pieces of glass which has been carefully cleaned, and on the middle of which a little Canada balsam has been dropped. The heat gradually loosens the cohesion of the slice, which is then very gently pushed with the needle or knife along to the contiguous clean slip of glass. Considerable practice is needed in this part of the work, as the slice, being so thin, is apt to go to pieces in being transferred. A gentle inclination of the warm plate, so that a tendency may be given to the slice to slip downwards of itself on to the clean glass, may be advantageously given. We must never attempt to lift the slice. All shifting of its position should be performed with the point of the needle or other sharp instrument. If it goes to pieces we may yet be able to pilot the fragments to their resting-place on the balsam of the new glass, and the resulting slide may be sufficient for the required purpose.

When the slice has been safely conducted to the centre of the glass slip, we put a little Canada balsam over it, and warm it as before. Then taking one of the thin cover-glasses with the forceps, we allow it gradually to rest upon the slice by letting down first one side, and then by degrees the whole. A few gentle circular movements of the cover-glass with the point of the needle or forceps may be needed to ensure the total disappearance of air-bubbles. When these do not appear, and when, as before, we find that the balsam has acquired the proper degree of consistence, the slide containing the slice is removed, and placed on the table with a small lead weight above it in the same way as already described. On becoming quite cold and hard, the superabundant balsam round the edge of the cover-glass may be scraped off with a knife, and any which still adheres to the glass may be removed with a little spirits of wine. Small labels should be kept ready for affixing to the slides to mark localities and reference numbers.[1] Thus labelled, the slide may be put away for future study and comparison.

[1] Where a number of slides are being prepared at once, it is convenient to distinguish

The whole process seems perhaps a little tedious. But in reality much of it is so mechanical, that after the mode of manipulation has been learnt by a little experience, the rubbing-down may be done while the operator is reading. Thus in the evening, when enjoying a pleasant book after his day in the field, he may at the same time, after some practice, rub down his rock-chips, and thus get over the drudgery of the operation almost unconsciously.

Boxes, with grooved sides or with flat trays for carrying microscopic slides, are sold in different sizes. Such boxes are most convenient for a travelling equipage, as they go into small space, and with the help of a little cotton-wool they hold the glass slides firmly without risk of breakage. For a final resting-place, a case with shallow trays or drawers in which the slides can lie flat is most convenient.

2. **The Microscope.**—Unless the observer proposes to enter into great detail in the investigation of the minuter parts of rock-structure, he does not require a large and expensive instrument. For most geological purposes, objectives of 2, 1, and ¼ inch focal length are sufficient. But it is desirable also for special work, such as the investigation of crystallites and inclusions of minerals, to have an objective capable of magnifying up to 200 or 300 diameters. An instrument with fairly good lenses of low powers, according to the arrangement of object-glasses and eye-pieces, may be had of some London makers for £5. But for some of the most important parts of the microscopical study of rocks, a rotating stage is requisite, the presence of which necessarily adds to the cost of the instrument. One of the best microscopes specially adapted for petrographical research is that devised by Mr. A. Dick, and manufactured by Swift and Son, of 81 Tottenham Court Road, London, price £18 without objectives.[1] Another instrument for petrographical work is constructed by the Bausch and Lomb Optical Company, Rochester, New York.[2]

Among the indispensable adjuncts are two Nicol-prisms, one (polariser) to be fitted below the stage, the other (analyser) most advantageously placed over the eye-piece. A quartz-wedge is useful in examination with polarised light. A nose-piece for two objectives, screwed to the foot of the tube, saves time and trouble by enabling the observer at once to pass from a low to a high power. The numerous pieces of apparatus necessary for physiological work are not needed in the examination of rocks and minerals.

3. **Methods of Examination.**—A few hints may be here given for the guidance of the student in making his own microscopic observations, but he must consult some of the special treatises mentioned on p. 119, for full details.

*Reflected Light.*—It is not infrequently desirable to observe with the microscope the characters of a rock as an opaque object. This cannot usually be done with a broken fragment of the stone, except of course with very low powers. Hence one of the most useful preliminary examinations of a prepared slice is to place it in the field, and, throwing the mirror out of gear, to converge as strong a light upon it as can be had, short of bright direct sunlight. The observer can then see some way into the rock and observe the relative thicknesses and forms of its constituents. The advantage of this method is particularly noticeable in the case of opaque minerals. The sulphides and iron-oxides so abundant in rocks appear as densely black objects with transmitted light, and show only their external form. But by throwing a strong light upon their surface, we may often discover not only their distinctive colours, but their characteristic internal structure. Titaniferous iron is an admirable example of the advantage of this method. Seen with transmitted light, that mineral appears in black, structureless grains or

them by engraving their numbers with a glazier's diamond on the glass. They are thus not liable to be confounded.

[1] *Mineral. Mag.* vol. viii. p. 160. A full description of the instrument by Mr. Dick is sold by Messrs. Swift and Son.

[2] G. H. Williams, *Amer. Journ. Sci.* xxxv. (1888), p. 114.

opaque patches, though frequently bounded by definite lines and angles. But with reflected light, the cleavage and lines of growth of the mineral can then often be clearly seen, and what seemed to be uniform black patches are found in many cases to enclose bright brassy kernels of pyrite. Magnetite also presents a characteristic blue-black colour, which distinguishes it from the other iron ores.

*Transmitted Light.*—It is, of course, with the light allowed to pass through prepared slices that most of the microscopic examination of minerals and rocks is performed. A little experience will show the learner that, in viewing objects in this way, he may obtain somewhat different results from two slices of the same rock according to their relative thinness. In the thicker one, a certain mineral or rock, obsidian for example, will appear perhaps brown or almost black, while in the other what is evidently the same substance may be pale yellow, green, brown, or almost colourless. Triclinic felspars seen in polarised light give only a pale milky light when extremely thin, but present bright chromatic bands when somewhat thicker.

*Polarised Light.*—By means of polarised light, an exceedingly delicate method of investigation is made available. We use both the Nicol-prisms. If the object be singly-refracting, such as a piece of glass, or an amorphous body, or a crystal belonging to some substance which crystallises in the isometric or cubic system (or if it be a tetragonal, hexagonal or rhombohedral crystal, cut perpendicular to its principal axis), the light will reach our eye apparently unaffected by the intervention of the object. The field will remain dark when the axes of the two prisms are at right angles (crossed Nicols), in the same way as if no intervening object were there. Such bodies are *isotropic.*[1] In all other cases, the substance is doubly-refracting and modifies the polarised beam of light. On rotating one of the prisms, we perceive bands or flashes of colour, and numerous lines appear which before were invisible. The field no longer remains dark when the two Nicol-prisms are crossed. Such a substance is *anisotropic.*

It is evident, therefore, that we may readily tell by this means whether or not a rock contains any glassy constituent. If it does, then that portion of its mass will become dark when the prisms are crossed, while the crystalline parts which, in the vast majority of cases, do not belong to the cubic system, will remain conspicuous by their brightness. A thin plate of quartz makes this separation of the glassy and crystalline parts of a rock even more satisfactory. It is placed between the Nicol-prisms, which may be so adjusted with reference to it that the field of the microscope appears uniformly violet. The glassy portion of any rock, being singly-refracting or isotropic, placed on the stage will allow the violet light to pass through unchanged, but the crystalline portions, being doubly-refracting or anisotropic, will alter the violet light into other prismatic colours. The object should be rotated in the field, and the eye should be kept steadily fixed upon one portion of the slide at a time, so that any change may be observed. This is an extremely delicate test for the presence of glassy and crystalline constituents.

In searching for the crystallographic system to which a mineral in a microscopic slide should be referred, attention is given to the directions in which the mineral placed between crossed Nicols appears dark, or to what are called the directions of its extinction. It is extinguished (that is, the normal darkness of the field between the crossed Nicols is restored) when two of its axes of elasticity for vibrations of light coincide with the principal sections of the two prisms. During a complete rotation of the slide in the field of the microscope the mineral becomes dark in four positions 90° apart, each of which marks that coincidence. When, on the other hand, the prisms are placed parallel to each other, the coincidence of their principal sections with the axes of elasticity in the mineral allows the maximum of light to pass through, which likewise occurs four

[1] But the effect of pressure-strain may give weak colour-tints in glasses and in cubic crystals. Professor Joly has devised an improved method of identifying crystals in rock-sections by the use of birefringence, *Sci. Proc. Roy. Dublin Soc.* ix. Part iv. No. 87 (1901). See also the work of MM. Michel-Lévy and Lacroix, cited on p. 119.

times in a complete rotation of the mineral. The different crystallographic systems are distinguishable by the relation between their crystallographic axes and their axes of elasticity. By noting this relation in the case of any given mineral (and there are usually sections enough of each mineral in the same rock-slice to furnish the required data) its crystalline system may be fixed. But in many cases it has been found possible to establish characteristic distinctions for individual mineral species, by noting the angle between the direction of their extinction and certain principal faces.

The determination of whether the component grains of a rock belong to uniaxial or biaxial doubly-refracting minerals is a point of much importance, which is effected by means of an achromatic condenser inserted in the aperture of the stage below the slide and suitably adjusted so as to converge the rays of light within the grain or crystal. The Nicols having been crossed, the eye-piece is removed, and the eye when held a little distance from the open end of the tube will perceive a dark bar, ring, or cross move across the field as the stage is rotated, if the mineral examined has been cut at a favourable angle. By the form and behaviour of these indications the uniaxial or biaxial character is made evident.

*Pleochroism* (*Dichroism*).—Some minerals show a change of colour when a Nicol-prism is rotated below them; hornblende, for example, exhibiting a gradation from deep brown to dark yellow. A mineral presenting this change is said to be pleochroic (polychroic, dichroic, trichroic). To ascertain the pleochroism of any mineral we remove the upper polarising prism (analyser) and leave only the lower (polariser). If as we rotate the latter, no change of tint can be observed, there is no pleochroic mineral present, or at least none which shows pleochroism at the angle at which it has been bisected in the slice. But in a slice of any crystalline rock, crystals may usually be observed which offer a change of hue as the prism goes round. These are examples of pleochroism. This behaviour may be used to detect the mineral constituents of rocks. Thus the two minerals hornblende and augite, which in so many respects resemble each other, cannot always be distinguished by cleavage angles, in microscopic slices. But as Tschermak pointed out, augite remains passive, or nearly so, as the lower prism is rotated: it is not pleochroic, or only very feebly so; while hornblende, on the other hand, especially in its darker varieties, is usually strongly pleochroic. It is to be observed, however, that the same mineral is not always equally pleochroic, and that the absence of this property is therefore less reliable as a negative test, than its presence is as a positive test.

It would be beyond the scope of this volume to enter into the complicated details of the microscopic structure of minerals and rocks. This information must be sought in some of the works specially devoted to it, a few of which are cited at p. 119.

In his examination of rocks with the microscope, the student may find an advantage in propounding to himself the following questions, and referring to the pages here cited.

1st, Is the rock entirely crystalline (pp. 127, 188, 195), consisting solely of crystals of different minerals interlaced; and if so, what are these minerals? 2nd, Is there any trace of a glassy ground-mass or base (pp. 131, 147)? Should this be detected, the rock is certainly of volcanic origin (pp. 213, 227, 235). 3rd, Can any evidence be found of the devitrification of what may have been at one time the glassy basis of the whole rock? This devitrification might be shown by the appearance of numerous microscopic hairs, rods, bundles of feather-like irregular or granular aggregations (p. 148). 4th, In what order did the minerals crystallise? This may often be made out with a microscope, as, for instance, where one mineral is enclosed within another (p. 146).[1] 5th, What is the nature of any alteration which the rock may have undergone? In a vast number of

[1] It is possible, however, that a crystal enclosed within another may sometimes have crystallised there out of a portion of the surrounding magma of the rock which has been enclosed within the larger crystal (*postea*, p. 146).

cases the slices show abundant evidence of such alteration: felspar passing into granular kaolin, augite changing into viridite, olivine into serpentine, while secondary calcite, epidote, quartz, and zeolites run in minute veins or fill up interstices of the rock (pp. 452-459). 6th, Is the rock a fragmental one; and if so, what is the nature of its component grains (p. 160 *et seq.*)? Is any trace of organic remains to be detected?

### Sect. iv.—General Outward or Megascopic (Macroscopic) Characters of Rocks.[1]

1. **Structure.**[2]—The different kinds of rock-structures distinguishable by the unaided eye are denoted either by ordinary descriptive adjectives, or by terms derived from rocks in which the special structures are characteristically developed, such as granitoid, brecciated, shaly. It must be borne in mind, however, that the external character of a rock does not always supply us with its true internal structure, which may be gained only by microscopic examination. This is of course more especially true of the close-grained kinds, where to the naked eye no definite structure is discernible. Some of the definitions originally founded on external appearance have been considerably modified by microscopic investigation. Many compact rocks, for instance, have been proved to be wholly crystalline.

The same rock-mass may show very different structures and textures in different parts of its extent. This is true alike of sedimentary and igneous materials. In the several portions of one continuous mass of erupted rock, variations in the rate of cooling, in temperature, and other circumstances have combined to produce sometimes the most extraordinary textural and even structural, as well as chemical and mineralogical contrasts.[3] Hence the student must be on his guard against concluding that two portions of rock strikingly unlike each other in outward appearance cannot be portions of one original continuous mass.

Crystalline (Phanerocrystalline), consisting wholly or chiefly of crystalline particles or crystals. If the whole of the substance of the original rock has assumed crystalline forms, whether or not these forms are bounded by crystalline faces, the structure is known as *holocrystalline.* The term *porphyritic-holocrystalline* has been applied by Rosenbusch to rocks having a finely crystalline base in which porphyritic crystals are

[1] The meanings of terms are generally more or less fully explained in petrographical text-books. Special treatises on this subject, however, have been prepared. See, for example, the "Lexique Pétrographique," prepared by Professor Loewinson-Lessing and published in the *Compt. rend.* of the 8th Session of the International Geological Congress, Paris 1901.

[2] In the 3rd edition of Jukes' 'Student's Manual of Geology' (1871), p. 93, it was proposed to reserve the term "Structure" for large features, such as characterise rock-blocks, and to use the term "Texture" for the minuter characters, such as can be judged of in hand specimens. M. De Lapparent makes a similar distinction ('Traité,' p. 619, *note*). But the practice of using the word structure as it is employed above in the text, has received such a support from the petrographers of Germany, that though I still think it would be preferable to distinguish between *texture* and *structure,* I have adopted what has now the sanction of common usage.

[3] See *postea,* p. 710 *et seq.;* G. F. Becker, *Amer. Journ. Sci.* xxxiii. (1887), p. 50. J. H. L. Vogt, *Geol. Fören. Förhand.*, Stockholm, xiii. (1891).

imbedded. *Crystalline-granular* denotes a base or ground-mass of this kind in which the whole of the ingredients have crystallised mostly in allotriomorphic forms, with no glassy base between them. Where the individual constituents are of large size, the structure is *coarse-crystalline* (*granitic*), as in many granites. When the particles are readily visible to the naked eye, and are tolerably uniform in size, as in marble, many granites and dolomites, the rock is said to be *granular crystalline*. Successive stages in the diminution of the size of the particles may be traced until these are no longer recognisable with the naked eye, and the structure must then be resolved with the microscope (*fine-crystalline, micro-crystalline, cryptocrystalline*). Fine-grained rocks may also be called *compact*, though this term is likewise applicable to the more close-grained varieties of the fragmental series. The microscopic characters of such rocks should always be ascertained where possible.[1]

Many crystalline rocks consist entirely or mainly of a magma or paste, the true nature of which it may be impossible, except from analogy, to determine megascopically. Such a ground-mass may be entirely composed of minute crystals, or partly of glass and partly of minerals that have crystallised out of the glass, or wholly of various crystallitic products of devitrification with or without (p. 129) phenocrysts of earlier consolidation. Its intimate structure can only be ascertained with the microscope. But its existence is often strikingly manifest even to the unassisted eye, for in what are termed "porphyries" it forms a large part of their mass. The term "*ground-mass*" is employed to denote this megascopic matrix. (See pp. 141-156.)

Lithoid, compact and stony in aspect, in opposition to vitreous; with no distinct crystalline structure. The term is especially applied to the devitrified condition of once glassy rocks, such as obsidians, which have assumed the character of perlites or rhyolites.

Granitic (Granitoid), thoroughly crystalline-granular, consisting of crystals or crystalline grains approximately uniform in size, as in granite. This structure is characteristic of many eruptive rocks. Though usually distinctly recognisable by the naked eye ("macromerite" of Vogelsang[2]), it sometimes becomes very fine ("micromerite"), and may be only recognisable with the microscope as thoroughly crystalline (microgranitic); at other times it passes into a porphyritic or porphyroid character by the appearance of large crystals dispersed through a general ground-mass.

Pegmatitic (Pegmatoid, Graphic, Granophyric), exhibiting the peculiar arrangement of crystalline constituents seen in pegmatite or graphic granite (p. 206), where the quartz and felspar have crystallised simultaneously, so as to be enclosed within each other.[3] This structure may be seen on a large scale in many massive veins of pegmatite; where it takes an exceedingly minute form it is known as micropegmatitic

[1] On the crystallisation of igneous rocks see J. P. Iddings, *Bull. Phil. Soc. Washington*, xi. (1889) p. 71.

[2] *Z. D. G. G.* xxiv. p. 534.

[3] This structure is grouped by Zirkel with a number of others (spherulitic, oolitic, &c.) as an "implication structure," 'Lehrbuch,' i. p. 469.

(Fig. 4). Such microscopic intergrowth of quartz and felspar is characteristic of large masses of eruptive rock (micropegmatite, granophyre).[1]

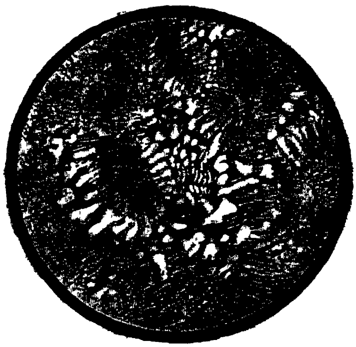


Fig. 4.—Micropegmatitic Structure. Granophyre, Mull. (Magnified.)

Aphanitic, a name given to the very close texture exhibited by some igneous rocks (diabases, diorites) where the component ingredients cannot be determined except with the microscope.

Porphyritic, composed of a compact or finely crystalline ground-mass, through which larger crystals of earlier consolidation, known as *phenocrysts*, often of felspar, are dispersed (Fig. 5).[2] This and the granitic structure are the two great structure-types of the eruptive rocks. By far the largest number of these rocks belong to the porphyritic type. Microscopic research has thrown much light on the nature of the ground-mass of porphyritic

Fig. 5.—Porphyritic Structure. (Nat. size.)

rocks. Vogelsang proposed to classify these rocks in three divisions:[3] 1st, *Granophyre*, where the ground-mass is a microscopic crystalline

[1] The late G. H. Williams proposed that the terms "poikilitic and micropoikilitic be employed for rock-structures, whether primary or secondary, conditioned by comparatively large individuals of one mineral enveloping smaller individuals of other minerals, which have no regular arrangement in respect to one another or to their host." The structure in question is, in a certain sense, intermediate between granular or microgranitic and graphic or micropegmatitic.

[2] Iddings, *Bull. Phil. Soc. Washington*, ii. (1889), p. 73; Whitman Cross, *14th Ann. Rep. U. S. G. S.* (1892-93), p. 232; Pirsson, *Amer. Jour. Sci.* vii. (1899), p. 272. The various significations attached to the term Porphyritic are well discussed by Zirkel in his 'Lehrbuch,' i. p. 465 *et seq.*

[3] Vogelsang, *loc. cit.* Compare the classification by Fouqué and Michel-Lévy, p. 196.

mixture of the component minerals with absence or sparing development of an imperfectly individualised magma (see p. 151); 2nd, *Felsophyre*, having usually an imperfectly individualised or felsitic magma for the ground-mass (pp. 149, 152); 3rd, *Vitrophyre*, where the ground-mass is a glassy magma (pp. 147, 153). The second subdivision embraces most of the porphyries, and a very large number of eruptive rocks of all ages.[1] The name Porphyroïd has been applied to such widely different rocks that it is not now much in use. By Lossen it was given to certain schistose, fibrous and porphyritic rocks belonging to the acid series of the crystalline schists, intermediate between hälleflinta and gneiss.[2] It has also been applied to metamorphosed sedimentary rocks, to coarse gneisses and granites, and to tuffs showing a porphyritic structure.

Segregated.—In granite and other crystalline massive rocks, vein-like portions, coarser (or finer) in texture than the rest of the mass, may be observed. These belong to the last phase of consolidation, when segregations from the original molten or viscous magma took place along certain lines or round particular centres, where the individual minerals crystallised out from the general mass. They have been sometimes termed "segregation," or "exudation" veins. They are to be distinguished from the veins, usually of finer and more acid material, which ramify through a mass of igneous rock and probably represent portions of the original molten magma which remained still liquid and were injected into rents of the already consolidated parts. (See "Contemporaneous Veins," p. 741.)

Granular.—This term has been somewhat loosely applied to any rocks composed of approximately equal grains, these grains being sometimes clastic fragments, as in greywacke and sandstone, sometimes crystalline particles, as in granite and marble. As applied to igneous rocks it is now used either by itself or with the prefix *crystalline*, to denote the holocrystalline character of such rocks as granite (see above, p. 128). The granular texture may become so fine as to pass insensibly into compact.[3] The peculiar granular structure found so abundantly among metamorphic rocks which have been intensely crushed, and in which there seems to have been a process of re-crystallisation among the powdered particles, has been termed granulitic (p. 258). This word, however, is liable to the objection that, while in England and in Germany it is applied to rocks bearing that structure, in France it is used for a holocrystalline granite.[4]

[1] According to Rosenbusch the porphyritic massive rocks are those in which, during the different stages of their production, the same minerals have been formed more than once. *Neues Jahrb.* 1882 (ii.), p. 14.

[2] *Z. D. G. G.* xxi. (1869), p. 329. See *postea*, p. 254.

[3] As applied to massive (eruptive) rocks, Rosenbusch would restrict the term granular to those in which each individual constituent separated out during but one definite stage of the process of rock-building. *Loc. cit.* On the use of this term, see Whitman Cross, *14th Ann. Rep. U. S. G. S.* (1892-93), p. 232.

[4] Michel-Lévy, *Ann. des Mines*, viii. (1875), p. 387; 'Structure et Classification des Roches éruptives,' 1889, p. 14; *postea*, pp. 196, 205.

Vitreous or glassy, having a structure like that of artificial glass, as in obsidian. Among crystalline eruptive rocks there is often present a variable amount of an amorphous ground-mass, which may increase until it forms the main part of the substance. The nature of this amorphous portion is described at pp. 147, 153. Its original condition has been that of a volcanic glass, now more or less devitrified. Most vitreous rocks present, even to the naked eye, dispersed grains, crystals, or other enclosures. Under the microscope, they are found to be often crowded with minute crystals and imperfect or incipient crystalline forms (p. 148). Resinous is the term applied to vitreous rocks having the lustre of pitchstone, and to others which are still less vitreous. Devitrification is the conversion of the vitreous into a crystalline or lithoid structure (pp. 148, 154).

Streaked, arranged in streaky inconstant lines either parallel or convergent, and often undulating (Fluctuationstructur). This structure, conspicuously shown by the lines of flow in vitreous rocks (flow-structure, fluxion-structure, fluidal structure), is less marked where the materials have assumed definite crystalline forms. It can be seen on a minute scale, however, in many crystalline masses when examined with the microscope (p. 153).[1]

Banded, arranged in parallel bands (schlieren), distinguished from each other by colour, texture, structure or composition; characteristic of many gneisses, of some large masses of gabbro where the rock appears to have come from a heterogeneous magma, and of jaspers, flints, hälleflintas and other flinty rocks. This term may often be applied to the flow-structure of igneous rocks referred to in the previous paragraph, likewise to the segregation veins of eruptive bosses and sheets, and to the parallel arrangement of materials produced in rocks, which, under intense mechanical pressure, have been crushed and sheared. With the naked eye it is often hardly possible to distinguish between the banded structure of devitrified igneous rocks and that resulting from the mechanical deformation here referred to.

Taxitic—a name proposed by Professor Loewinson-Lessing to denote an arrangement in volcanic rocks in the crystallisation of which two products have arisen distinct from each other in structure, colour, or composition. These rocks are thus in appearance clastic, but are really of primitive origin. When the different portions of the taxite are disposed in alternate bands, they are called *Eutaxites;* when they occur in angular fragments dispersed in the matrix without definite order like a breccia, they form *Ataxites.* It is a kind of liquation in filamentous bands. As synonymous terms the author of the name cites "Spaltungsbreccia," "Tufflava," "Piperno," "Trümmerporphyre," &c.[2]

Spherulitic, composed of incipient crystallisations of minerals which diverge from one or more points and terminate outwardly at nearly the same distance from the centre, so as to produce globules, spherules, or larger accretions of usually globular forms, which are marked by the

[1] On this structure see E. Weiss, 'Beiträge zur Kenntniss der Feldspathbildung,' Haarlem, 1866, p. 143; Vogelsang, 'Philosophie der Geologie,' 1867, p. 138; Zirkel, *Z. D. G. G.* 1867, p. 742.

[2] *Bull. Soc. Belg. Géol.* v. p. 104; *Compt. rend.* Internat. Geol. Congress, Paris, 1900, p. 1280.

internal radiation of divergent fibres or rods from the central starting-point (Figs. 6, 16). Sometimes the centre is a phenocryst, in other cases no foreign nucleus can be detected. The structure occurs in vitreous rocks and forms an important stage in the devitrification of obsidian, pitchstone, &c. The crystallisation appears to be largely due to the intergrowth of quartz and felspar in a minute micropegmatitic aggregate. Sometimes the spherules are hollow, but show the fibrous divergent structure in their outer shells. Spherulites exist of all sizes, from microscopic proportions up to masses ten feet in diameter. Where the fibres, instead of radiating from a centre, diverge from a line such as a crack, the structure has been termed by Zirkel axiolitic.[1]

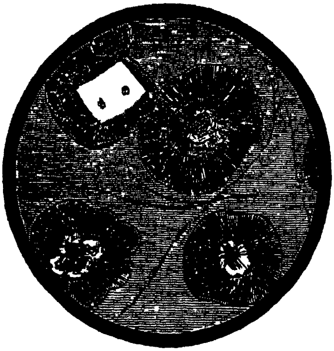


Fig. 6.—Spherulitic Structure. (Magnified.)

The term lithophyse has been applied by F. von Richthofen to large

Fig. 7.—Orbicular Structure. Napoleonite, Corsica. (Nat. size.)

bladder-like spherulites wherein interspaces lined with crystals occur

[1] Vogelsang was the first to make a microscopic study of spherulites. He distinguished among them cumulites, globospherites, granospherites, belonospherites and felsospherites, *Archiv Nêerland.* vii. 1872; 'Die Krystalliten,' 1875. See also Delesse, *Mém. Soc. Géol. France*, iv. (1852); *B. S. G. F.* ix. (1852), p. 431; Whitman Cross, *Phil. Soc. Washington*, xi. p. 411 (1891); J. P. Iddings, *op. cit.* p. 445, and *7th Ann. Rep. U. S. Geol. Surv.* (1888), p. 254. Quartz assumes in some rocks (*e.g.* banded eurites) a finely globular structure which was developed before the cessation of the motion that produced flow-structure, and which, according to M. Michel-Lévy, may be regarded as connecting the colloid and crystallised conditions of silica. *Bull. Soc. Géol. France* (3), v. (1877), p. 257. Also *Compt. rend.* xciv. (1882), p. 464. The formation of spherulites is further referred to at p. 153, and also in Book IV. Part VII.

between the successive concentric internal layers.[1] Many ancient rhyolites present an aggregate of nodular bodies (Pyromeride) due originally to devitrification and subsequently more or less altered, especially by the deposition of silica within them.

Orbicular structure is one in which the component minerals of a rock have crystallised in such a way as to form spheroidal aggregations, sometimes with an internal radial or concentric grouping. It is typically seen in the corsite, napoleonite, or ball-diorite (Kugel-diorit, orbicular diorite, p. 224) of Corsica (Fig. 7), but occurs in other rocks, sometimes even in granite.[2]

Perlitic (Figs. 8 and 19), having the structure of the rock formerly termed perlite, wherein between minute rectilinear fissures the substance of the mass has assumed, during the contraction resulting from cooling, a finely globular character, not unlike the spheroidal structure seen in weathered basalt, which is also a phenomenon of contraction during the cooling and consolidation of an igneous rock.[3]

Fig. 8.—Perlitic Structure. (Magnified.)

Horny, flinty, having a compact, homogeneous, dull texture, like that of horn or flint, as in chalcedony, jasper, flint, and many hälleflintas and felsites.

Cavernous (porous), containing irregular cavities due, in most cases, to the abstraction of some of the minerals; but occasionally, as in some limestones (sinters), dolomites and lavas, forming part of the original structure of the rock.

Cellular.—Many lavas, ancient and modern, have been saturated with steam at the time of their eruption, and in consequence of the segregation and expansion of this imprisoned vapour, have had spherical cavities developed in their mass. When this cellular structure is marked by comparatively few and small holes, it may be called vesicular; where the rock consists partly of a roughly cellular, and partly of a more compact substance intermingled, as in the slag of an iron furnace, it is said to be slaggy; portions where the cells occupy about as much space as the solid part, and vary much in size and shape, are called scoriaceous, this being the character of the rough clinker-like scoriæ of recent lava-streams; when the cells are so much more numerous than the solid part, that the stone would originally have almost or quite floated on water,

[1] *Jahrb. K. K. Geol. Reichsanst.* 1860, p. 180. See Iddings, *7th Ann. Rep. U. S. Geol. Surv.* (1885-86), p. 249. *Amer. Journ. Sci.* xxxiii. (1887), p. 36. G. A. Cole and G. W. Butler, *Q. J. G. S.* xlvii. (1892), p. 438, and *postea*, p. 215. On hollow spherulites, Parkinson, *Q. J. G. S.* lvii. (1900), p. 211.

[2] Fine examples of this structure have been obtained from the granites of Sweden and the north-west of Ireland. See p. 206.

[3] Professor Watts has described perlitic cracks developed in quartz, *Q. J. G. S.* l. (1894), p. 367.

the structure is called pumiceous, *pumice* being the froth-like part of lava. As the cellular structure can only be developed while the rock is still liquid, or at least viscid, and as, while in this condition, the mass is often still moving away from its point of emission, the cells are not infrequently elongated in the direction of movement. Subsequently, water infiltrating through the rock, deposits various mineral substances (calcite, quartz, chalcedony, zeolites, &c.) from solution, so that the flattened and elongated almond-shaped cells are eventually filled up. A cellular rock which has undergone this change is said to be an amygdaloid, or amygdaloidal, and the almond-like kernels are known

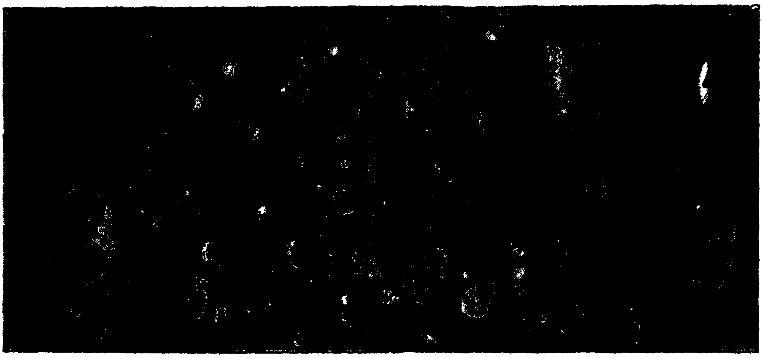


Fig. 9.—Amygdaloidal Structures; Porphyrite, Old Red Sandstone, Ayrshire. (Nat. size.)

as amygdales (Fig. 9). Where the cells or cavernous spaces of a rock are lined with crystals and empty inside they are said to be druses or drusy cavities. Some igneous rocks (certain granites, &c.) are full of small irregularly shaped cavities into which the constituent minerals may project with crystallographic forms. Such a structure is termed miarolitic.

Cleaved, having a fissile structure superinduced by pressure and known as Cleavage (see pp. 417, 684). The planes of cleavage are independent of those of bedding, though they may sometimes coincide with them. A cleaved structure is best seen in fine-grained material, and is typically developed in roofing-slate, but it may occur in any compact igneous rock (p. 418).

Foliated, consisting of minerals that have crystallised in approximately parallel, lenticular, and usually wavy layers or folia. Rocks of this kind commonly contain layers of mica, or of some equivalent readily cleavable mineral, the cleavage-planes of which coincide generally with the planes of foliation (p. 244). Gneiss, mica-schist and talc-schist are characteristic examples. So distinctive, indeed, is this structure in schists, that it is often spoken of as schistose. In gneiss, it attains its most massive form; in chlorite-schist and some other schists, it becomes so fine as to pass into a kind of minutely scaly texture, often only perceptible with the microscope, the rock having on the whole a massive structure.

Fibrous, consisting of one or more minerals composed of distinct fibres. Sometimes the fibres are remarkably regular and parallel, as in fibrous gypsum, and veins of chrysotile, fibrous aragonite or calcite (satin-spar); in other instances, they are more tufted and irregular, as in asbestos and actinolite-schist.

Cataclastic, Mylonitic, terms introduced to denote the peculiar granular structure of rocks which have undergone intense crushing, such as has taken place along lines of fracture and movement, as in faults and thrust-planes. The materials have been reduced to minute grains which have not re-crystallised as they have done in the granulitic structure.

Clastic, fragmental, composed of detritus (p. 154). Rocks possessing this character have, in the great majority of cases, been formed in water, and their component fragments are usually more or less rounded or water-worn. Different names are applied, according to the form or size of the fragments. Brecciated, composed, like a breccia, of angular fragments, which may be of any degree of coarseness. Agglomerated, consisting of large, roughly rounded and tumultuously grouped blocks, as in the agglomerate filling old volcanic funnels. Conglomerated (Conglomeratic), made up of well-rounded blocks or pebbles; rocks having this character have been formed by and deposited in water. Pebbly, containing dispersed water-worn pebbles, as in many coarse sandstones, which thus by degrees pass into conglomerates. Psammitic, or sandstone-like, composed of rounded grains, as in ordinary sandstone: when the grains are larger (often sharp and somewhat angular) the rock is gritty, or a grit. Muddy (pelitic), having a texture like that of dried mud. Cryptoclastic or compact, where the grains are too minute to reveal to the naked eye the truly fragmental character of the rock, as in fine mudstones and other argillaceous deposits.

Concretionary, containing or consisting of mineral matter, which has been collected, either from the surrounding rock or from without, round some centre, so as to form a nodule or irregularly shaped lump. This aggregation of material is of frequent occurrence among water-formed rocks, where it may be often observed to have taken place round some organic centre, such as a leaf, cone, shell, fish-bone, or other relic of plant or animal. (Book IV. Part I.) Among the most frequent minerals found in concretionary forms as constituents of rocks, are calcite, siderite, pyrite, marcasite, and various forms of silica. In a true concretion, the material at the centre has been deposited first, and has increased by additions from without, either during the formation of the enclosing rock, or by subsequent concentration and aggregation. Where, on the other hand, cavities and fissures have been filled up by the deposition of materials on their walls, and gradual growth inward, the result is known as a secretion. Amygdales and the successive coatings of mineral veins are examples of the latter process.

Dendritic—a name applied to arborescent deposits, usually of some dark metallic oxide (especially of iron and manganese), which are formed through the agency of infiltrating water along the joints or other smooth divisional planes of minerals and rocks (Fig. 220). Occasionally these

dendrites present so strong a resemblance to vegetable forms as to be readily mistaken for fossil plants. Landscape-marble owes its peculiar appearance to a variety of this structure (p. 649).

Septarian—a structure often exhibited by concretions of limestone and clay-ironstone which in consolidating have shrunk and cracked internally. These shrinkage-cracks radiate in an irregular way from the middle towards the circumference, but die out before reaching the latter (Fig. 25). Usually they have been filled with some subsequently infiltrated mineral, notably calcite.

Oolitic, a structure like fish-roe, formed of spherical grains, each of which has an internal radiating and concentric structure, and often possesses a central nucleus of some foreign body. This structure is specially found among limestones (see p. 191).[1] When the grains are as large as peas, the structure is termed pisolitic.

Various structures which affect large masses of rock rather than hand-specimens will be found described in Book IV. But a few of the more important may be included here.

Massive, unstratified, having no arrangement in definite layers or strata. Lava, granite, and generally all crystalline rocks which have been erupted to the surface, or have solidified below from a state of fusion, are massive rocks.

Stratified, bedded, composed of layers or beds lying parallel to each other, as in shale, sandstone, limestone, and other rocks which have been deposited in water. Successive streams of lava, poured one upon another, have also a bedded arrangement. Laminated, consisting of fine, leaf-like strata or laminæ; this structure being characteristically exhibited in shales, is sometimes also called shaly.

Jointed, traversed by the divisional planes termed Joints, which are fully treated of in Book IV. Part II.

Columnar, divided into prismatic joints or columns. This structure is typically represented among the basalts and other basic lavas (p. 663 and Figs. 235-237, 335, 338), but it may also be observed as an effect of contact-metamorphism among stratified rocks which have been invaded by intrusive masses (p. 769).

Pillow-structure (Ellipsoidal structure)—an arrangement in many ancient and modern lavas where the rock before consolidating has separated into globular or pillow-shaped blocks from a few inches to several yards in diameter. The outer shell of these spheroids or ellipsoids is sometimes closer grained than the inside, and has rows of small vesicles running parallel to the outer surface. In the interstices between the blocks various sedimentary materials have sometimes been introduced, such as volcanic tuff, sandstone, shale, ironstone or chert (see p. 760).

2. **Composition.**—Before having recourse to chemical or microscopic analysis, the geologist can often pronounce as to the general chemical or mineralogical nature of a rock. Most of the terms which he employs to

[1] See Mr. Wethered's paper in *Q. J. G. S.* li. (1895), p. 196.

express his opinion are derived from the names of minerals, and in almost all cases are self-explanatory. The following examples may suffice. Calcareous, consisting of or containing carbonate of lime. Argillaceous, consisting of or containing clay. Felspathic, having some form of felspar as a main constituent. Siliceous, formed of or containing silica; usually applied to the chalcedonic forms of this cementing oxide. Quartzose, containing or consisting entirely of some form of quartz. Carbonaceous, containing coaly matter, and hence usually associated with a dark colour. Pyritous, containing diffused disulphide of iron. Gypseous, containing layers, nodules, strings or crystals of calcium-sulphate. Saliferous, containing beds of, or impregnated with rock-salt. Micaceous, full of layers of mica-flakes.

As rocks are not definite chemical compounds, but mixtures of different minerals in varying proportions, they exhibit many intermediate varieties. Transitions of this kind are denoted by such phrases as "granitic gneiss," that is, a gneiss in which the normal foliated structure is nearly merged into the massive structure of granite; "argillaceous limestone"—a rock in which the limestone is mixed with clay; "calcareous shale"—a fissile rock, consisting of clay with a proportion of lime.

As already alluded to, and as will be more fully explained in later pages, the progress of research goes to show that even in the same mass of eruptive rock considerable differences of chemical composition may be found. These differences seem to point to some separation of the constituents, before consolidation. Thus the picrite of Bathgate shades upwards into a rock in which the heavy magnesian silicates are replaced in large measure by felspars.[1] Mr. Iddings has called attention to some remarkable gradations of composition among the volcanic rocks of the Tewar mountains, New Mexico, where he believes a series of intermediate varieties to be traceable from obsidian at the one end to basalt at the other.[2] A remarkable instance of a similar kind has been described by Mr. Teall and Mr. Dakyns from the Scottish Highlands.[3] Many examples have now been cited both in the Old and New Worlds, where an acid eruptive boss passes laterally into highly basic material, granite, for instance, graduating towards the margin into gabbro and serpentine. This subject is further discussed at p. 710 *et seq.*

3. **State of Aggregation.**—The hardness or softness of a rock—in other words, its induration, friability, or the degree of aggregation of its particles—may be either original or acquired. Some rocks (sinters, for example) are soft at first and harden by degrees; the general effect of exposure, however, is to loosen the cohesion of the particles of rocks. A rock which can easily be scratched with the nail is almost always much decomposed, though some chloritic and talcose schists are soft enough to be thus affected. Compact rocks which can easily be scratched with the

[1] *Trans. Roy. Soc. Edin.* vol. xxix. (1879), p. 504.

[2] *Bull. U. S. G. S.* No. 66 (1890); *Bull. Phil. Soc. Washington*, xi. (1890), pp. 65, 191; and *postea*, pp. 708, 710.

[3] Teall and Dakyns, *Q. J. G. S.* 1892.

knife, and are apparently not decomposed, may be fine-grained limestones, dolomites, ironstones, mudstones, or some other simple rocks. Crystalline rocks, except limestones and dolomites, cannot, as a rule, be scratched with the knife unless considerable force be used. They are chiefly composed of hard silicates, so that when an instance occurs where a fresh specimen can be easily scratched, it will usually be found to be a limestone (pp. 112, 176, 190). The ease with which a rock may be broken is the measure of its frangibility. Most rocks break most easily in one direction; attention to this point will sometimes throw light upon their internal structure.

Fracture is the surface produced when a rock is split or broken, and depends for its character upon the texture of the mass. Finely granular, compact rocks are apt to break with a splintery fracture where wedge-shaped plates adhere by their thicker ends to, and lie parallel with, the general surface. When the rock breaks off into concave and convex rounded shell-like surfaces, the fracture is said to be conchoidal, as may be seen in obsidian, flint, and exceedingly compact limestones. The fracture may also be foliated, slaty, or shaly, according to the structure of the rock. Many opaque, compact rocks are translucent on the thin edges of fracture, and afford there, with the aid of a lens, a glimpse of their internal composition. A rock is said to be flinty, when it is hard, close-grained, and breaks with a smooth or conchoidal fracture like flint; friable, when it crumbles down like dry clay or chalk; plastic, when, like moist clay, it can be worked into shapes between the fingers; pulverulent, when it falls readily to powder; earthy, when it is decomposed into loam or earth; incoherent or loose, when its particles are quite separate, as in dry blown sand.

4. **Colour and Lustre.**—These characters vary so much, even in the same rock, according to the freshness of the surface examined, that they possess but a subordinate value. Nevertheless, when cautiously used, colour may be made to afford valuable indications as to the probable nature and composition of rocks. It is, in this respect, always desirable to compare a freshly broken with a weathered piece of the rock. Some minerals and rocks lose their distinctive tints on being heated, and even on being exposed to sunlight. In some cases these evanescent colours are doubtless due to organic compounds, which are broken up by heat; in others their origin is not quite clear.[1]

*White* indicates usually the absence or a comparatively small amount of the heavy metallic oxides, especially iron. It may either be the original colour, as in chalk and calc-sinter, or may be developed by weathering, as in the white crust on flints and on many porphyries. *Grey* is a frequent colour of rocks which, if quite pure, would be white, but which acquire a greyish tint by admixture of dark silicates, organic matter,

[1] See Jannettaz, *B. S. G. F.* xxix. (1872), p. 300. The non-organic nature of the evanescent colours is maintained by E. Weinschenk, *Z. D. G. G.* xlviii. (1896), p. 704; *Zeitsch. Anorg. Chemie*, xii. (1896), p. 375; *Zeitsch. Kryst.* xxviii. (1897), p. 135; *Tschermak's Mittheil.* xix. (1900), p. 144; the other and more general view is upheld by L. Wöhler and K. v. Kraatz-Koschlau, *Tschermak's Mittheil.* xviii. pp. 304, 447.

diffused pyrites, &c. *Blue*, or *bluish-grey*, is a characteristic tint of rocks through which iron-disulphide is diffused in extremely minute subdivision. But as a rule it rapidly disappears from such rocks on exposure, especially where they contain organic matter also. The stiff blue clay of the sea-bottom, which is coloured by iron-disulphide, becomes reddish-brown when dried, and then shows no trace of sulphide.[1] *Black* may be due either to the presence of carbon (when weathering will not change it much), or to some iron-oxide (magnetite chiefly), or some silicate rich in iron (as hornblende and augite). Many rocks (basalts and melaphyres particularly) which look quite black on a fresh surface, become red, brown or yellow on exposure, black being comparatively seldom a weathered colour. *Yellow* (or *Orange*), as a dull earthy colouring matter, almost always indicates the presence of hydrated peroxide of iron. In modern volcanic districts it may be due to iron-chloride, sulphur, &c. Bright, metallic, gold-like yellow is usually that of iron-disulphide. *Brown* is the normal colour of some carbonaceous rocks (lignite), and ferruginous deposits (bog-iron-ore, clay-ironstone, &c.). It very generally, on weathered surfaces, points to the oxidation and hydration of minerals containing iron. *Red*, in the vast majority of cases, is due to the presence of anhydrous peroxide of iron. This mineral gives dark blood-red to pale flesh-red tints. As it is liable, however, to hydration, these hues are often mixed with the brown, orange and yellow colours of limonite.[2] *Green*, as the prevailing tint of rocks, occurs amongst schists, when its presence is usually due to some of the hydrous magnesian silicates (chlorite, talc, serpentine). It appears also among massive rocks, especially those of older geological formations, where hornblende, olivine, or other silicates have been altered (as in "greenstone"). Among the sedimentary rocks, it is principally due to ferrous silicate (as in glauconite). Carbonate of copper colours some rocks emerald- or verdigris-green. The mottled character so common among many stratified rocks is frequently traceable to unequal weathering, some portions of the iron being more oxidised than others; while some, on the other hand, become deoxidised from the reducing action of decaying organic matter, as in the circular green spots so often found among red strata.

Lustre, as an external character of rocks, does not possess the value which it has among minerals. In most rocks, the granular texture prevents the appearance of any distinct lustre. A completely *vitreous* lustre without a granular texture, is characteristic of volcanic glass. A *splendent semi-metallic* lustre may often be observed upon the foliation planes of schistose rocks and upon the laminæ of micaceous sandstones. As this silvery lustre is almost invariably due to the presence of mica, it is commonly called distinctively *micaceous*. A *metallic* lustre is met with sometimes in beds of anthracite; more usually its occurrence among rocks indicates the presence of metallic oxides or sulphides. A *resinous* lustre is characteristic of many pitchstones. *Lustre-mottling* is a term applied to the interrupted sheen on the cleavage faces of minerals, which have

[1] J. Y. Buchanan, *Brit. Assoc.* 1881, p. 584.

[2] See I. C. Russell, *B. U. S. G. S.* No. 52 (1889).

enclosed much smaller crystals or grains of other minerals. It is well seen on the surfaces of some of the constituents of serpentine rocks.

5. **Feel and Smell.**—These minor characters are occasionally useful. By the feel of a mineral or rock is meant the sensation experienced when the fingers are passed across its surface. Thus hydrous magnesian silicates have often a marked soapy or greasy feel. Some sericitic mica-schists show the same character. Trachyte received its name from its characteristic rough or harsh feel. Some rocks adhere to the tongue, a quality indicative of their tendency to absorb water.

Smell.—Many rocks, when freshly broken, emit distinctive odours. Those containing volatile hydrocarbons give sometimes an appreciable *bituminous* odour, as is the case with certain eruptive rocks, which in central Scotland have been intruded through coal-seams and carbonaceous shales. Limestones have often a *fetid* odour; rocks full of decomposing sulphides are apt to give a *sulphurous* odour; those which are highly siliceous yield, on being struck, an *empyreumatic* odour. It is characteristic of argillaceous rocks to emit a strong earthy smell when breathed upon.

6. **Specific Gravity.**—This is an important character among rocks as well as among minerals. It varies from 0·6 among the hydrocarbon compounds to 3·1 among the basalts. As already stated, the average specific gravity of the rocks of the earth's crust may be taken to be about 2·5, or from that to 3·0. Instruments for taking the specific gravity of rocks have been already (p. 114) referred to.

7. **Magnetism** is so strongly exhibited by some crystalline rocks as powerfully to affect the magnetic needle, and to vitiate observations with this instrument. It is due to the presence of magnetic iron, the existence of which may be shown by pulverising the rock in an agate mortar, washing carefully the triturated powder, and drying the heavy residue, from which grains of magnetite or of titaniferous magnetic iron may be extracted with a magnet. This may be done with any basalt (p. 234). A freely swinging magnetic needle is of service, as by its attraction or repulsion it affords a delicate test for the presence of even a small quantity of magnetic iron.

### Sect. v. Microscopic Characters of Rocks.

No department of Geology has advanced so rapidly in recent years as Lithology, and this has been mainly due to the introduction of the microscope as an instrument for investigating the minute internal structures of rocks. Though the method of mounting thin slices on glass devised by William Nicol was made known to the world in 1831, it was not until 1856 that the full value of the method was recognised by Mr. Sorby and made known to geologists in the epoch-making papers which have been already alluded to (p. 119). Reference will be made in subsequent pages to the remarkable results then announced by him. To the publication of the paper of 1858 the subsequent rapid development of the study of rocks may be distinctly traced. The microscopic

method of analysis is now in use in every country where attention is paid to the history of rocks.

Information has already been given (p. 119 *et seq.*) regarding the preparation of sections of rocks for microscopical examination, the methods of procedure in the practice of this part of geological research, and some of the terms employed in the following pages.

### 1. *Microscopic Elements of Rocks.*

Rocks when examined in thin sections with the microscope are found to be composed of or to contain various elements, of which the more important are, 1st, crystals, or crystalline grains; 2nd, glass; 3rd, crystallites; 4th, detritus.

A. CRYSTALS OR CRYSTALLINE GRAINS.—Rock-forming minerals, when not amorphous, may be either crystallised in their proper crystallographic forms (idiomorphic, automorphic), or, while possessing a crystalline internal structure, may present no definite external geometrical form (allotriomorphic, xenomorphic, p. 89). The latter condition is more prevalent, seeing that minerals have usually been developed round and against each other, thus mutually hindering the assumption of determinate crystallographic contours. Other causes of imperfection are fracture by movement in the original magma of the rock, and partial solution in that magma (Fig. 11), as in the corroded quartz of quartz-porphyries and rhyolites, and the hornblende crystals of basalts. The ferro-magnesian minerals of earlier consolidation among basalts and andesites are sometimes surrounded with a dark shell called the corrosion-zone. In some rocks, such as granite, the thoroughly crystalline character of the component ingredients is well marked, yet they less frequently present the definite isolated crystals so often to be observed in porphyries and in many old and modern volcanic rocks. Among thoroughly crystalline rocks, good crystals of the component minerals may be obtained from fissures and cavities in which there has been room for their formation. It is in the "drusy" cavities of granite, for example. that the well-defined prisms of felspar, quartz, mica, topaz, beryl and other minerals are found. Successive stages in order of appearance or development can readily be observed among the crystals of rocks. Some appear as large, but frequently broken or corroded forms. These have evidently been formed first. Others are smaller but abundant, usually unbroken, and often disposed in lines. Others have been developed by subsequent alteration within the rock.[1]

A study of the internal structure of crystals throws light not merely on their own genesis, but on that of the rocks of which they form part, and is therefore well worthy of the attention of the geologist. That many apparently simple crystals are in reality compound, may not infrequently be detected by the different condition of weathering in the two opposite parts of a twin on an exposed face of rock. The internal structure of a crystal modifies the action of solvents on its exterior (*e.g.* weathered

[1] Fouqué and Michel-Lévy, 'Min. Micrograph,' p. 151.

surfaces of calcite, aragonite and felspars). Crystals may occasionally be observed built up of rudimentary "microlites," as if these were the simplest forms in which the molecules of a mineral began to appear (p. 148).

A microscopic examination of some rocks shows that a subsequent or secondary growth of different minerals has taken place after their original crystalline form was complete. These later additions are in optical continuity with the original crystal, and sometimes have taken place even upon worn or imperfect forms. They may be occasionally detected among the silicates of igneous rocks, and also even among the sandgrains of sandstones which have thus had their rounded forms converted into crystallographic faces.[1]

Crystalline minerals are seldom free from extraneous inclusions. These are occasionally large enough to be readily seen by the naked eye. But the microscope reveals them in many minerals in almost incredible quantity. They are, $\alpha$, vesicles containing gas; $\beta$, vesicles containing liquid; $\gamma$, globules of glass or of some lithoid substance; $\delta$, crystals; $\epsilon$, filaments, or other indefinitely shaped pieces, patches, or streaks of mineral matter.

$\alpha$. Gas-filled cavities are most frequently globular or elliptical, and appear to be due to the presence of gas or steam in the crystal at the time of consolidation. Zirkel estimates those minute pores at 360,000,000 in a cubic millimetre of the hauyne from Melfi.[2] In some instances the cavity has a geometric form belonging to the crystalline system of the enclosing mineral. Such a space defined by crystallographic contours is a *negative crystal*. A cavity filled with gas contains no bubble, and its margin is marked by a broad dark band. The usual gases are hydrogen, carbon-dioxide, carbon-monoxide, marsh-gas and nitrogen. In experiments recently made by Professor Tilden[3] it was found that various rocks contain many times their own volume of these gases, as shown in the following examples:—

| | Volume of Gas per Volume of Rock. | Composition of Gas in 100 Volumes. $CO_2$ | $H_2$, &c. |
|---|---|---|---|
| Granite (Tertiary), Skye | 2·8 | 11·5 | 88·5 |
| Granite (Palæozoic), Ardsheil | 6·9 | 79·5 | 20·5 |
| Gabbro (Tertiary), Skye | 3·5 | 21·6 | 78·4 |
| Gabbro (Palæozoic), Lizard | 6·4 | trace. | 100·0 |
| Basalt (Tertiary), Antrim | 8·0 | 32·0 | 68·0 |
| Quartzite (Cambrian), Sutherland | 2·2 | 14·3 | 85·7 |
| Gneiss with Corundum, Seringapatam | 17·8 | 18·0 | 82·0 |

More detailed study of the gases showed that by much the most abundant of them is hydrogen, and that carbon-dioxide comes next, followed by variable proportions of carbonic oxide, marsh-gas, and

[1] H. C. Sorby, Presidential Address, Geol. Soc. 1880, p. 62. R. D. Irving and C. R. Van Hise, 'On Secondary Enlargements of Mineral Fragments in certain Rocks,' *B. U. S. G. S.* No. 8 (1884). J. W. Judd, *Q. J. G. S.* xlv. (1889), p. 175.

[2] 'Mik. Beschaff.' p. 86.

[3] *Proc. Roy. Soc.* lix. (1896), p. 223; lx. (1897), p. 453. See also a paper by Prof. W. Ramsay in same volume.

nitrogen, as shown in the subjoined table. The gases appear to be wholly enclosed in the cavities, which are so minute that little is lost by pounding a rock into fragments.

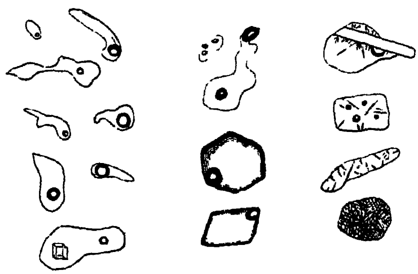
| | $CO_2$ | CO | $CH_4$ | $N_2$ | $H_2$ |
|---|---|---|---|---|---|
| Granite from Skye . . | 23·60 | 6·45 | 3·02 | 5·13 | 61·68 |
| Gabbro from Lizard . . | 5·50 | 2·16 | 2·03 | 1·90 | 88·42 |
| Gneiss, Seringapatam . . | 31 62 | 5·36 | 0·51 | 0·56 | 61·93 |
| Basalt from Antrim . . | 32·08 | 20 08 | 10·00 | 1·61 | 36·15 |

*β.* Vesicles containing liquid (and gas).—As far back as the year 1823, Brewster studied the nature of certain fluid-bearing cavities in different minerals.[1] The first observer who showed their important bearing on geological researches into the origin of crystalline rocks was Mr. Sorby, in whose paper, already cited, they occupy a prominent place. They are frequently abundant in quartz, felspars, topaz, emerald, sapphire, gypsum, rock-salt, and other minerals and rocks. Vesicles entirely filled with liquid are distinguished by their sharply defined and narrow black borders. Vesicular spaces containing fluid may be noticed in many artificial crystals formed from aqueous solutions (crystals of common salt show them well) and in many minerals of crystalline rocks. They are exceedingly various in form, being branching, curved, oval, or spherical, and sometimes assuming as negative crystals a geometric form, like that characteristic of the mineral in which they occur, as cubic in rock-salt and hexagonal in quartz. They also vary greatly in size. While occasionally in quartz, sapphire, and other minerals, large cavities are readily observable with the naked eye, they may be traced with high magnifying powers down to less than $\frac{1}{10000}$th of an inch in diameter. Their proportion in any one crystal ranges within such wide limits, that whereas in some crystals of quartz few may be observed, in others they are so minute and abundant that many millions must be contained in a cubic inch. The fluid present is usually water, often with solutions of salts or of gas, chloride of sodium or of potash, or sulphates of potash, soda or lime being specially frequent. Carbon-dioxide may be present in the water, or exist by itself in the liquid condition. Sometimes the cavities are partially occupied with it in liquid form, and the two fluids, as originally observed by Brewster, may be seen in the same cavity unmingled, the carbon-dioxide remaining as a freely moving globule within the carbonated water.[2] Cubic crystals of

[1] *Edin. Phil. Journ.* ix. p. 94. *Trans. Roy. Soc. Edin.* x. p. 1. See also W. Nicol, *Edin. New Phil. Journ.* (1828), v. p. 94; De la Vallée Poussin and Renard, *Acad. Roy. Belg.* 1876, p. 41; Hartley, *Journ. Chem. Soc.* ser. 2, xiv. p. 137; ser. 3, ii. p. 241; *Microscop. Journ.* xv. p. 170; *Brit. Assoc.* 1877, Sect. p. 232.

[2] See Sorby, *Proc. Roy. Soc.* xvii. (1869), pp. 295, 301. Vogelsang thought it more probable that there is only one liquid consisting of water charged with carbonic acid, the globule consisting of the carbon dioxide in the gaseous form. *Poggend. Ann.* cxxxvii. p. 69. Liquid carbon dioxide has been recognised as the fluid filling many of the cavities in crystals. Simmler, *Poggend. Ann.* cv. p. 460; Vogelsang and Geissler, *op. cit.* cxxxvii. (1869), pp. 56, 265; Sorby, *Proc. Roy. Soc.* xvii. (1869), p. 291. G. W. Hawes has described a remarkable instance in the quartz of a pegmatite vein in Connecticut where the

chloride of sodium may be occasionally observed in the fluid, which must in such cases be a saturated solution of this salt (Fig. 10, lowest figure in Column A). Usually each cavity contains a small globule or bubble, sometimes stationary, sometimes movable from one side or end of the cavity to the other, as the specimen is turned. With a high magnifying power, the minuter bubbles may be observed to be in motion, sometimes slowly pulsating from side to side, or rapidly vibrating like a living organism. The cause of this trepidation, which resembles the so-called "Brownian movements," has been plausibly explained by the incessant interchange of the molecules from the liquid to the vaporous condition along the surface where vapours and liquid meet—an interchange which, though not visible on the large bubbles, makes itself apparent in the minute examples, of which the dimensions are comparable to those of the intermolecular spaces.[1] The bubble may be made to disappear by the application of heat.



B C

Fig. 10.—Cavities in Crystals highly magnified A, Liquid Inclusions; B, Glass Inclusions; C, Cavities showing the devitrification of the original glass by the appearance of crystals, &c., until in the lowest figure a stony or lithoid product is formed.

With regard to the origin of the bubble, Sorby pointed out that it can be imitated in artificial crystals, in which he explained its existence by diminution of volume of the liquid owing to a lowering of temperature after its enclosure. By a series of experiments he ascertained the rate of expansion of water and saline solutions up to a temperature of 200° C. (392° Fahr.), and calculated from them the temperature at which the liquid in crystals would entirely fill its enclosing cavities. Thus, in the nepheline of the ejected blocks of Monte Somma, he found that the relative size of the vacuities was about ·28 of the fluid, and assuming the pressure under which the crystals were formed to have been not much greater than sufficient to counteract the elastic force of the vapour, he concluded that the nepheline may have been formed at a temperature of about 340° C. (644° Fahr.), or a very dull red heat, only just visible in the dark. He estimated also from the fluid cavities in the

outer zone of the cavity consists of water, the middle zone of liquid carbonic dioxide, and the inner globule of the acid in gaseous form, *Amer. Journ. Sci.* xxi. (1881), p. 204. Mr. A. W. Wright has determined that the gases in the cavities of smoky quartz consist of $CO_2$ 98·33 per cent, N 1·67; with traces of $H_2S$, $SO_2$, $H_2N$, and doubtfully Cl. *Op. cit.* p. 216.

[1] Charbonelle and Thirion, *Rev. Quest. Scientifi.* vii. (1880), p. 48; G. W. Hawes, *Amer. Journ. Sci.* xxi. (1881), p. 203; A. W. Wright, *ibid.* p. 209; Von Lasaulx and A. Renard, *Sitzb. Niederrhein. Ges. Bonn* (1874), p. 254. On the critical point of water, &c., in these cavities, see Hartley, *Journ. Chem. Soc.* ser. 3, ii. p. 241. See also *Pop. Sci. Rev.* new ser. i. p. 119; *Proc. Roy. Soc.* xxvi. (1875), pp. 137, 150.

quartz of granite that this rock has probably consolidated at somewhat similar temperatures, under a pressure sometimes equal to that of 76,000 feet of rock.[1] Zirkel, however, has pointed out that even in contiguous cavities, where there is no evidence of leakage through fine fissures, the relative size of the vacuole varies within very wide limits, and in such a manner as to indicate no relation whatever to the dimensions of the enclosing cavities. Had the vacuole been due merely to the contraction of the liquid on cooling, it ought to have always been proportionate to the size of the cavity.[2]

MM. De la Vallée Poussin and Renard, attacking the question from another side, measured the relative dimensions of the vesicle and of its enclosed water and cube of rock-salt, as contained in the quartziferous diorite of Quenast in Belgium. The temperature at which the ascertained volume of water in the cavity would dissolve its salt was found by calculation to be 307° C. (520° Fahr.). But as the law of the solubility of common salt had not been experimentally determined for high temperatures, this figure could only be accepted provisionally, though other considerations went to indicate that it is probably not far from the truth. Assuming then that this was the temperature at which the vesicle was formed, these authors proceeded to determine the pressure necessary to prevent the complete vaporisation of the water at that temperature, and obtained, as the result, a pressure of 87 atmospheres, equal to 84 tons per square foot of surface.[3] That many rocks were formed under great pressure is well shown by the liquid carbon-dioxide in the pores of their crystals.

Although, perhaps, in most cases, the liquid inclusions are to be referred to the conditions under which the minerals containing them crystallised out of the original magma, they have in some cases evidently been developed long subsequently by a process of internal solution, either in one of the original minerals during decomposition, or in a mineral of secondary origin, such as quartz of subsequent introduction.[4]

Liquid inclusions may be dispersed at random through a crystal, or, as in the quartz of granite, gathered in intersecting planes (which look like fine fissures and which may sometimes have become real fissures, owing to the line of weakness caused by the crowding of the cavities), or disposed regularly in reference to the contour of the crystal. In the last case they are sometimes confined to the centre, sometimes arranged in zones along the lines of growth of the crystal.[5] In this form they are

[1] Sorby, *Quart. Journ. Geol. Soc.* xiv. pp. 480, 493.

[2] 'Mik. Beschaff.' p. 46.

[3] "Mémoire sur les Roches dites Plutoniennes de la Belgique," De la Vallée Poussin and A. Renard, *Acad. Roy. Belg.* 1876, p. 41. See also Ward, *Q. J. G. S.* xxxi. p. 568, who believed that the granites of Cumberland consolidated at a maximum depth of 22,000 to 30,000 feet.

[4] See Whitman Cross on the development of liquid inclusions in plagioclase during the decomposition of the gneiss of Brittany, *Tschermak's Min. Mittheil.* 1880, p. 369; also G. F. Becker, "Geology of Comstock Lode," *U. S. G. S.* 1882, p. 371.

[5] The way in which vesicles, enclosed crystals, &c., are grouped along the zones of growth of crystals is illustrated in Fig. 11.

specially conspicuous in the quartz of granite and other massive rocks, as well as of gneiss and mica-schist.

γ. Inclusions of glass or of some lithoid substance.—In many rocks which have consolidated from fusion, the component crystals contain globules or irregularly shaped enclosures of a vitreous nature (Fig. 10, Column B). These enclosures are analogous to the fluid-inclusions just described. They are portions of the original glassy magma out of which the minerals of the rock crystallised, as portions of the mother-liquor are enclosed in artificially formed crystals of common salt. That magma is in reality a liquid at high temperatures, though at ordinary temperatures it becomes a solid. At first, these glass-vesicles may be confounded with the true liquid-cavities, which in some respects they closely resemble. But they may be distinguished by the immobility of their bubbles, of which several are sometimes present in the same cavity; by the absence of any diminution of the bubbles when heat is applied; by the elongated shape of many of the bubbles; by the occasional extrusion of a bubble almost beyond the walls of the vesicle; by the usual pale greenish or brownish tint of the substance filling the vesicle, and its identity with that forming the surrounding base or ground-mass in which the crystals are imbedded; and by the complete passivity of the substance in polarised light (see p. 125).

Glass inclusions occur abundantly in some minerals, aggregated in the centre of a crystal or ranged along its zones of growth with singular regularity. They appear in felspars, quartz, leucite, and other crystalline ingredients of volcanic rocks, and of course prove that in such positions these minerals, even the refractory quartz, have undoubtedly crystallised out of molten solutions.

In inclusions of a truly vitreous nature, traces of devitrification may not infrequently be seen. In particular, microscopic crystallites (p. 148) make their appearance, like those in the ground-mass of the rock. Sometimes the inclusions, like the general ground-mass, have an entirely stony character (Fig. 10, C). This may be well observed in those which have not been entirely separated from the surrounding ground-mass, but are connected with it by a narrow neck at the periphery of the enclosing crystal. In some granites and in elvans, the quartz by irregular contraction, while still in a plastic state, appears to have drawn into its substance portions of the surrounding already lithoid base;[1] but this appearance may sometimes be due to irregular corrosion of the crystals by the magma.[2]

δ. Crystals and crystalline bodies.—Many component minerals of rocks contain other minerals (Fig. 11). These occur sometimes as perfect crystals, more usually as what are termed microlites (p. 148). Like the glass-inclusions, they tend to range themselves in lines along the successive zones of growth in the enclosing mineral. Microlites are of frequent occurrence in leucite, garnet, augite, hornblende, calcite, fluorite, &c. From the fact that microlites of the easily fusible augite

[1] J. A. Phillips, *Q. J. G. S.* xxxi. p. 338.

[2] Fouqué and Michel-Lévy, 'Min. Micrograph.

are, in the Vesuvian lavas, enclosed within the extremely refractory leucite, it was supposed that the relative order of fusibility is not always followed in the microlites and enveloping crystals. But this has been satisfactorily explained by MM. Fouqué and Michel-Lévy, who have shown experimentally that leucite, when crystallising from fusion, tends to catch up inclusions of the surrounding glass, which, should the glass be pyroxenic, may assume the form of augite.[1]

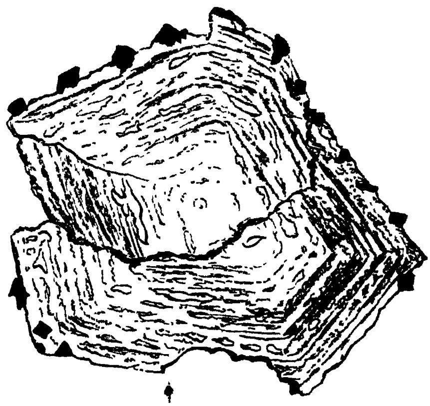


Fig. 11.—Section of a fractured and corroded Augite Crystal from a dyke, Crawfordjohn, Lanarkshire (magnified), showing lines of growth with vesicles and magnetite crystals.

ε. Filaments, streaks, patches, discolorations.—Besides the enclosures already enumerated, crystals likewise frequently enclose irregular portions of mineral matter, due to alteration of the original substance of the minerals or rocks. Thus tufts and vermicular aggregates of certain green ferruginous silicates are of common occurrence among the crystals and cavities of old pyroxenic volcanic rocks. Orthoclase crystals are often mottled with patches of a granular nature, due to partial conversion of the mineral into kaolin. The magnetite, so frequently enclosed within minerals, is abundantly oxidised, and has given rise to brown and yellow patches and discolorations. The titaniferous iron has often been altered and partially replaced by amorphous streaks and patches of leucoxene. Care must be taken not to confound these results of infiltrating water with the original characters of a rock. Practice will give the student confidence in distinguishing them, if he familiarises his eye with decomposition products by studying slices or the powder of weathered minerals and of the weathered parts of rocks.

B. Glass.—Even to the unassisted eye, many volcanic rocks consist obviously in whole or in great measure of glass.[2] This substance in mass is usually black or dark green, but when examined in thin sections under the microscope it presents for the most part a pale brown tint, or is nearly colourless. In its purest condition it is quite structureless, that is, it contains no crystals, crystallites, or other distinguishable individualised bodies. But even in this state it may sometimes be observed to be marked by clot-like patches or streaks of darker and lighter tint, arranged in lines or eddy-like curves, indicative of the flow of the original fluid mass. Rotated in the dark field of crossed Nicol-prisms, such a natural glass remains dark, as, unless where it has undergone internal stresses, it is perfectly inert in polarised light. Being thus

[1] 'Synthèse des Minéraux,' 1882, p. 155.

[2] See E. Cohen on Glassy Rocks, *Neues Jahrb.* 1880 (ii.), p. 23.

*isotropic*, it may readily be distinguished from any enclosed crystals which, acting on the light, are *anisotropic* (p. 125). Perfectly homogeneous structureless glass, without enclosures of any kind, occurs for the most part only in limited patches, even in the most thoroughly vitreous rocks. Originally the structure of all glassy rocks, at the time of most complete fusion, may have been that of perfectly unindividualised glass. But as these masses tended towards a solid form, devitrification of their glass set in. Many forms of incipient or imperfect crystallisation, as well as perfect crystals, were developed in the still fluid and moving mass, and, together with crystals of earlier growth, were arranged in the direction of motion. Devitrification has in frequent examples proceeded so far that no trace remains of any actual glass.[1]

C. Crystallites and Microlites.[2]—Under these names may be included minute inorganic bodies possessing a more or less definite form, but generally without the geometrical characters of crystals. They occur most commonly in rocks which have been formed from igneous fusion, but are found also in others which have resulted from, or have been altered by, aqueous solutions. They seem to be early or peculiar forms of crystallisation. They are abundantly developed in artificial slags, and appear in many modern and ancient vitreous rocks, but the conditions under which they are produced are not yet well understood.[3]

Crystallites are distinguished by remaining isotropic in polarised light. The simplest are extremely minute drop-like bodies or *globulites*, sometimes crowded confusedly through the glass, giving it a dull or somewhat granular character, while in other cases they are arranged in lines or groups. Gradations can be traced from spherical or spheroidal globulites into other forms more elliptical in shape, but still having a rounded outline and sometimes sharp ends (*longulites*). There does not appear to be any essential distinction, save in degree of development, between these forms and the long rod-like or needle-shaped bodies which have been termed *belonites*. Existing sometimes as mere simple needles or rods, these more elongated crystallites may be traced into more complex forms, curved or coiled, at one time solitary, at another in groups. In most cases, crystallites are transparent and colourless, or slightly tinted, but sometimes they are black and opaque, from a coating of ferruginous oxide, or only appear so as an optical delusion from their position. Black, seemingly opaque, hair-like, twisted and curved forms, termed *trichites*, occur abundantly in obsidian.

[1] Consult a paper on the microscopic character of devitrified glass and some analogous rock-structures, by D. Herman and F. Rutley, *Proc. Roy. Soc.* 1885, p. 87.

[2] The word *crystallite* was first used by Sir James Hall to denote the lithoid substance obtained by him after fusing and then slowly cooling various "whinstones" (diabases, &c.). Since its revival in lithology it has been applied to the minuter bodies above described. The student should consult Vogelsang's 'Philosophie der Geologie,' p. 139; 'Krystalliten,' Bonn, 8vo, 1875; also his descriptions in *Archives Néerlandaises*, v. 1870, vi. 1871. Sorby, *Brit. Assoc.* 1880. Vogelsang was the first to describe and classify these minute objects.

[3] They are well exhibited also in ordinary blow-pipe beads. See Sorby, *Brit. Assoc.* 1880, or *Geol. Mag.* 1880, p. 468. They have been produced experimentally in the artificial rocks fused by MM. Fouqué and Michel-Lévy.

Microlites are other incipient forms of crystallisation which differ from crystallites in that they react on polarised light. They assume rod-like or needle-shaped forms sometimes occurring singly, sometimes in aggregates, and even occasionally grouped into skeleton crystals. They can for the most part be identified as rudimentary forms of definite minerals, such as augite, hornblende, felspar, olivine, and magnetite.

Good illustrations of the general character and grouping of crystallites and microlites are shown in some vitreous basalts and andesites. Thus in

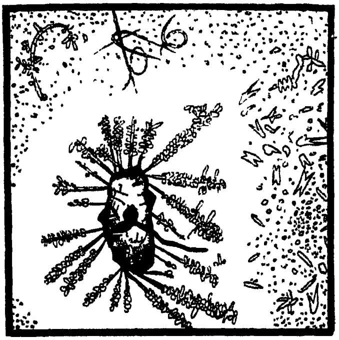


Fig. 12.—Augite Crystal surrounded by Crystallites and Microlites, from the vitreous Andesite of Eskdalemuir, magnified 800 diameters.

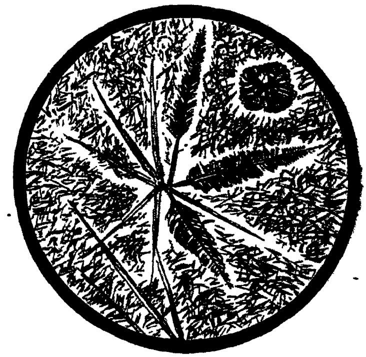


Fig. 13.—Microlites and Crystallites of the Pitchstone of Arran, magnified 70 diameters. (See p. 216.)

Fig. 12 the outer portion of the field displays crowded globulites and longulites, as well as here and there a few belonites and some curved and coiled trichites. Round the rude augite crystal, these various bodies have been drawn together out of the surrounding glass. Numerous rod-like microlites diverge from the crystal, and these are more or less thickly crusted with the simpler and smaller forms.[1] In Fig. 13, the remarkably beautiful structure of an Arran pitchstone is shown; the glassy base being crowded with minute microlites of hornblende which are grouped in a fine feathery or brush-like arrangement round tapering rods. In this case, also, we see that the glassy base has been clarified round the larger individuals by the abstraction of the crowded smaller microlites. By the progressive development of crystallites, microlites, or crystals during the cooling and consolidation of a molten rock, a glass loses its vitreous character and becomes lithoid; in other words, undergoes devitrification.

The characteristic amorphous or indefinitely granular and fibrous or scaly matter, constituting the microscopic base in which the definite crystals of felsites and porphyries are imbedded (pp. 209, 216), has been the subject of much discussion. Between crossed Nicol-prisms it sometimes behaves isotropically, like a glass, but in other cases allows a mottled glimmering light to pass through. It is now well understood to be a product of the devitrification of once glassy rocks wherein the

[1] *Proc. Roy. Phys. Soc. Edin.* v. p. 246, Plate v. Fig. 5. J. J. H. Teall, *Q. J. G. S.* xl. p. 221, Plate xii. Fig. 2a.

crystallitic and microlitic forms can still be recognised or have been more or less effaced by subsequent alteration by infiltrating water.[1]

Every gradation in the relative abundance of crystallites may be traced. In some obsidians and other vitreous rocks, portions of the glass can be obtained with comparatively few of them; but in the same rocks we may not infrequently observe adjacent parts where they have been so largely developed as to usurp the place of the original glass, and give the rock in consequence a lithoid aspect (Fig. 10, C, and pp. 210-216).

D. DETRITUS.—Many rocks are composed of the detritus of pre-existing materials. In the great majority of cases this can be readily detected, even with the naked eye. But where the texture of such detrital or fragmental (clastic) rocks becomes exceedingly fine, their true nature may require elucidation with the microscope (Figs. 20, 21). An obvious distinction can be drawn between a mass of compact detritus and a crystalline or vitreous rock. The detrital materials are found to consist of various and irregularly shaped grains, with more or less of an amorphous and generally granular paste. In some cases the grains are broken and angular, in others they are rounded or waterworn (pp. 164, 166). They may consist of minerals (quartz, chert, felspars, mica, &c.), or of rocks (slate, limestone, basalt, &c.), or of the remains of plants or animals (spores of lycopods, fragments of shells, crinoids, &c.). It is evident therefore that though some of them may be crystalline, the rock of which they now form part is a non-crystalline compound. Water, with carbonate of lime or other mineral matter in solution, permeating a detrital rock, has sometimes allowed its dissolved materials to crystallise among the interstices of the detritus, thus producing a more or less distinctly crystalline structure. But the fundamentally secondary or derivative nature of the mass is not always thereby effaced.[2]

## 2. *Microscopic Structures of Rocks.*

We have next to consider the manner in which the foregoing microscopic elements are associated in rocks. This inquiry brings before us the minute structure or texture of rocks, and throws great light upon their origin and history.[3]

Four types of rock-structure are revealed by the microscope:—A, holocrystalline; B, hemi-crystalline; C, glassy; D, clastic.

A. HOLOCRYSTALLINE, consisting entirely of crystals or crystalline individuals, whether visible to the naked eye, or requiring the aid of a microscope, imbedded in each other without any intervening amorphous substance. Rocks of this type are exemplified by granite (Figs. 14 and 28) and by other igneous rocks. But they occur also among the crystalline

[1] See Zirkel, 'Mik. Beschaff.' p. 280. Rosenbusch, 'Mikroskop. Phys.' vol. ii.

[2] On the microscopic character of detrital rocks consult the volume of M. Cayeux, cited *ante*, p. 106; also the manuals of Zirkel and Rosenbusch.

[3] The first broad classification of the microscopic structures of rocks was that proposed by Zirkel, which, with slight modification, is here adopted. 'Mik. Beschaff.' p. 265; 'Basaltgesteine,' p. 88; 'Lehrbuch,' i. p. 686. See also Rosenbusch's suggestive paper already cited, *Neues Jahrb.* 1882 (ii.), p. 1.

limestones and schists, as in statuary marble, which consists entirely of crystalline granules of calcite (Fig. 27). Professor Zirkel recognises the following three varieties in this type of structure.[1]

(1) No constituent is more prominent than another either as to form or size. In some cases the whole of the minerals are of nearly equal dimensions, entirely or almost entirely allotriomorphic (xenomorphic) in shape, and vary in size from coarse granular, as in many granites, down to microscopic fineness. This is the "granitic structure" of M. Michel-Lévy, and the "hypidiomorphic structure" of Professor Rosenbusch. In other cases, a pegmatitic intergrowth of the minerals, especially quartz and felspar, pervades the rock and gives rise to the "pegmatoid" or "micropegmatitic" structure of the former petrographer, and the "granophyric" structure of the latter.

(2) Some constituents are conspicuous above the rest by their more automorphic (idiomorphic) forms. This may arise in a rock of tolerably uniform grain by the appearance of crystals with some of their crystallographic faces developed ("granulitic" of Michel-Lévy, "panidiomorphic" of Rosenbusch); or where the felspar-laths have some other crystalline mineral squeezed, as it were, in between them, giving rise to the "intersertal" or "ophitic" structure.

(3) Certain of the constituents stand out by their size (and form) above the other smaller crystalline ingredients of the aggregate, giving rise to varieties of the porphyritic structure.

As the holocrystalline eruptive rocks (p. 195) are typically represented by granite, the term *granitoid* has been used to express their microscopic

Fig. 14.—Holocrystalline Structure. Granite (20 diameters). The white portions are Quartz, the striped parts Felspar, the long, dark, finely striated stripes are Mica. (See p. 204.)

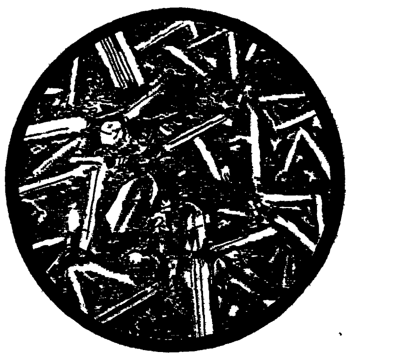


Fig. 15.—Hemi-crystalline Structure. Dolerite, consisting of a triclinic Felspar, Augite, and Magnetite in a devitrified ground-mass (20 diameters). The numerous narrow prisms are triclinic Felspar; the broader monoclinic forms, slightly shaded in the drawing, are Augite; the black specks are Magnetite; the needle-shaped forms are Apatite. (See p. 233.)

structure. Where their elements are minute, the structure becomes *micrograntoid* or *euritic*, and can in many cases only be distinguished from *felsitic* by microscopic examination. Empty (miarolitic, p. 134) cavities have been left during the consolidation of some igneous rocks. Minute

[1] 'Lehrbuch,' i. p. 688.

interspaces between the crystalline grains of a rock characterise the *saccharoid* structure (Fig 27).[1]

B. Hemi-crystalline.[2]—This division probably comprehends the majority of the massive eruptive or igneous rocks. It is distinguished by the occurrence of what appears to the naked eye as a compact or finely granular ground-mass, through which more or less recognisable crystals are scattered. Examined with the microscope, this ground-mass is found to present considerable diversity (Figs. 15, 17, 31). It may be (1) wholly a glass, as in some basalts, trachytes, and other volcanic products; (2) partly devitrified through separation of peculiar little granules and needles (crystallites and microlites) which appear in a vitreous base; (3) still further devitrified, until it becomes an aggregation of such little granules, needles, and hairs, between which little or no glass-base appears (microcrystallitic); or (4) "microfelsitic" (petrosiliceous), closely related to the two previous groups, and consisting of a nearly structureless mass, marked usually with indefinite or half-effaced granules and filaments,

Fig. 16.—Microspherulitic Structure. Pitchstone, Raasay (magnified).

A

B

Fig. 17.—Intersertal or Ophitic Structure. A. Dolerite, Skye (magnified). B. Dolerite, Gortacloghan, Co. Derry (magnified).

but behaving like a singly-refracting, amorphous body (p. 149).

[1] Fouqué and Michel-Lévy, 'Min. Micrograph.' The micropegmatite of Michel-Lévy is the same as the structure subsequently named granophyre by Rosenbusch. Michel-Lévy, 'Roches éruptives,' p. 19.

[2] For this structure the term "mixed" has been proposed, as being a mixture of the crystalline and amorphous (glassy) structures. It has been designated by Fouqué and Michel-Lévy "trachytoid," as being typically developed among the trachytes (*postea*, p. 226). It is called "hypocrystalline" by Rosenbusch.

In rocks belonging to this type, a *spherulitic* structure has sometimes been produced by the appearance of globular bodies composed of a crystalline internally radiating substance, sometimes with concentric shell of amorphous material. Spherulites are sometimes so minute as to be only recognisable with the microscope, when they each present a black cross between crossed Nicol-prisms, and thereby characteristically reveal the *microspherulitic* structure (Figs. 6 and 16).[1]

The term intersertal (Zirkel, 1870) or ophitic (Fouqué and Michel-Lévy, 1879), already mentioned, is applied to a structure in which one mineral after crystallising has been enclosed within another during the consolidation of an igneous rock (Fig. 17). It is abundant in many dolerites and diabases where some bisilicate such as augite serves as a matrix in which the felspars and other crystals are enclosed. The name "ophitic" is derived from the so-called "ophites" of the Pyrenees.[2]

C. GLASSY.—Composed of a volcanic glass such as has already been described. It seldom happens, however, that rocks which seem to the eye to be tolerably homogeneous glass do not contain abundant crystallites and minute crystals. Hence entirely vitreous rocks are of comparatively rare occurrence, and where representatives of them do locally occur they are apt to graduate into the second or hemi-crystalline type. This gradation and the abundant traces of a devitrified base or magma between the crystals of a vast number of eruptive rocks, lead to the belief that the glassy type was the original condition of most if not all of these rocks. Erupted as molten masses, their mobility would depend upon the fluidity of the glass. Yet even while still deep within the earth's crust, some of their constituent minerals (felspars, leucite, magnetite, &c.) were often already crystallised, and suffered fracture and corrosion by subsequent action of the enclosing magma. Hence, where the magma has subsequently crystallised we can distinguish between the earlier crystals (first consolidation) and those of the later time (second consolidation). There may thus be two generations of felspar in the same rock. The older crystals are usually larger than those of subsequent growth.

The movement of the magma in glassy rocks is often well shown by *flow-structure* (*fluxion-*, *fluctuation-*, *fluidal structure*), already referred to. Crystals and crystallites are ranged in current-like lines, with their long axes in the direction of these lines. Where a large older crystal occurs, the train of minuter individuals is found to sweep round it and to reunite on the further side, or to be diverted in an eddy-like course, with occasional involutions and contortions (Fig. 18). So thoroughly is this arrangement characteristic of the motion of a some-

[1] Fouqué and Michel-Lévy, 'Min. Micrograph.' Some remarkably beautiful examples of microspherulitic structure occur in the quartz-porphyries that traverse the lower Cambrian tuffs at St. David's. *Q. J. G. S.* xxxix. p. 313.

[2] These rocks (which are connected with the diabases) have been critically studied by Michel-Lévy, *B. S. G. F.* vi. (1877), p. 156; x. (1882); Caralp, 'Etudes géologiques sur les hauts Massifs des Pyrénées centrales,' Toulouse, 1888; J. Kühn, *Z. D. G. G.* xxxiii. (1881), p. 372; Dieulafait, *Compt. rend.* xciv. (1882), p. 667; xcvii. (1883), p. 1089; Lacroix, *op. cit.* cx. (1890), p. 1011; *Bull. Soc. Min. France*, xiv. (1891), p. 30; J. Seunes, *Ann. Mines*, xviii. (1890), p. 484.

what viscid liquid, that there cannot be any doubt that such was the condition of these masses before their consolidation. This flow-structure may be detected in many eruptive rocks, from thoroughly vitreous compounds like obsidian, on the one hand, to completely crystalline masses like some dolerites, on the other. It occurs not only in what are usually regarded as volcanic rocks, but also in plutonic or deep-seated masses which, there is reason to believe, consolidated beneath the surface. An instance was described by Lossen in the Bode vein of the Harz. Many other examples have since been found among quartz-porphyries associated with granites in Aberdeenshire, in felsite dykes and bosses in the Shetlands, Skye, and southern Ireland, and among the basic dykes of central and western Scotland. The structure, therefore, cannot be regarded as

Fig. 18.—Flow-structure in Obsidian (20 diameters).

Fig. 19.—Perlitic Structure. Felsitic glass, Mull (magnified).

of itself affording any presumption that the rock in which it is found ever flowed out at the surface as lava.

Some glassy rocks, in cooling and consolidating, have had spherulites developed in them (Fig. 16); also by contraction the system of reticulated and spiral cracks known as *perlitic* structure (p. 133, and Figs. 8 and 19).

The final stiffening of a vitreous mass into solid stone has resulted (1st) from mere solidification of the glass: this is well seen at the edge of dykes and intrusive sheets of different basalt-rocks, where the igneous mass, having been suddenly congealed along its line of contact with the surrounding rocks, remains there in the condition of glass, though only an inch farther inward from the chilled edge the vitreous magma has disappeared, as represented in Fig. 306; (2nd) from the devitrification of the glass by the abundant development of microfelsitic granules and filaments, as in quartz-porphyry, or of crystallites, microlites and crystals, as in such glassy rocks as obsidian and tachylite; or (3rd) from the more or less complete crystallisation of the original glassy base, as may be observed in some dolerites.

D. Clastic.—Composed of detrital materials, such as have been already described (pp. 135, 150, and Fig. 20). Where these materials consist of grains of quartz-sand, they withstand almost any subsequent

change, and hence can be recognised even among a highly metamorphosed series of rocks. Quartzite from such a series can sometimes be scarcely distinguished under the microscope from unaltered quartzose sandstone. Where the detritus has resulted from the destruction of aluminous or magnesian silicates, it is more susceptible of alteration. Hence it can be traced in regions of local metamorphism, becoming more and more crystalline, until the rocks formed of or containing it pass into true crystalline schists.

Detritus derived from the comminution or decay of organic remains presents very different and characteristic structures (Fig. 21). Sometimes it is of a siliceous nature, as where it has been derived from diatoms and radiolarians. But most of the organically derived detrital

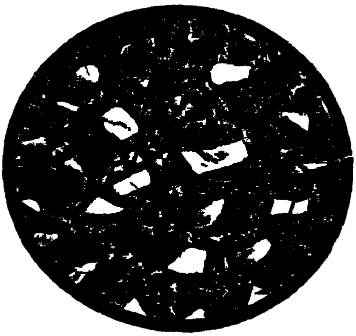


Fig. 20.—Clastic Structure, of Inorganic Origin—Section of a piece of Greywacke. (10 diameters. See p. 166.)

Fig. 21.—Clastic Structure, of Organic Origin—Structure of Chalk (Sorby). (Magnified 100 diameters. See p. 179.)

rocks are calcareous, formed from the remains of foraminifera, corals, echinoderms, polyzoa, cirripedes, annelides, mollusks, crustacea and other invertebrates, with occasional traces of fishes or even of higher vertebrates. Distinct differences of microscopic structure can be detected in the hard parts of some of the living representatives of these forms, and similar differences have been detected in beds of limestone of all ages. Mr. Sorby, in a paper already cited, has shown how characteristic and persistent are some of these distinctions, and how they may be made to indicate the origin of the rock in which they occur.[1] There is an important difference between the two forms in which carbonate of lime is made use of by invertebrate animals; aragonite being much less durable than calcite (pp. 106, 177). Hence, while shells of gasteropods, many lamellibranchs, corals and other organisms, formed largely or wholly of aragonite, crumble down into mere amorphous mud, pass into

[1] The student who would further investigate this subject should consult the suggestive and luminous essay by Mr. Sorby in his Presidential Address to the Geological Society, *Q. J. G. S.* 1879. The microscopic characters of a series of Mesozoic and Tertiary detrital rocks are given by Dr. L. Cayeux in his 'Contribution à l'Étude micrographique des Terrains sédimentaires,' Lille, 1897. Further details in this subject will be found in subsequent pages of this volume (pp. 176-179).

crystalline calcite, or disappear, the fragments of those consisting of calcite may remain quite recognisable.

It is evident, therefore, that the absence of all trace of organic structure in a limestone need not invalidate an inference from other evidence that the rock has been formed from the remains of organisms. The calcareous organic débris of a sea-bottom may be disintegrated, and reduced to amorphous detritus, by the mechanical action of waves and currents, by the solvent chemical action of the water, by the decay of the binding material, such as the organic matter of shells, or by being swallowed and digested by other animals (*postea*, pp. 602, 614).[1]

Moreover, in clastic calcareous rocks, owing to their liability to alteration by infiltrating water, there is a tendency to acquire an internal crystalline texture (p. 474). At the time of formation, little empty spaces lie between the component granules and fragments, and according to Mr. Sorby these interspaces may amount to about a quarter of the whole mass of the rock. They have very commonly been filled up by calcite introduced in solution. This infiltrated calcite acquires a crystalline structure, like that of ordinary mineral-veins. But the original component organic granules also themselves become crystalline, and, save in so far as their external contour may reveal their original organic source, they cannot be distinguished from mere mineral-grains. In this way a cycle of geological change is completed. The calcium-carbonate originally dissolved out of rocks by infiltrating water, and carried into the sea, is secreted from the oceanic waters by corals, foraminifera, echinoderms, mollusks and other invertebrates. The remains of these creatures collected on the sea-bottom slowly accumulate into beds of detritus, which in after times are upheaved into land. Water once more percolating through the calcareous mass, gradually imparts to it a crystalline structure, and eventually all trace of organic forms may be effaced. But at the same time the rock, once exposed to meteoric influences, is attacked by carbonated water, its molecules are carried in solution into the sea, where they will again be built up into the frame-work of marine organisms.

**Alteration of Rocks by Meteoric Water.**—In connection with the discussion of the minute structures discoverable in rocks, reference may be made here to the important revelations of the microscope as to the extent to which rocks suffer from the influence of infiltrating water. The nature of some of these changes will be more fully described in subsequent pages. (Book III. Part II. Sect. ii. § 2.) Among the more obvious proofs of alteration are the threads and kernels of calcite in such eruptive rocks as diabase, dolerite or andesite. These furnish a good index of internal decomposition, usually arising from the decay of some lime-bearing mineral in the rock. Some other minerals are likewise frequent signs of alteration, such as serpentine (often resulting from the alteration of olivine (Figs. 32, 33)), chlorite, epidote, limonite, chalcedony, &c. In

[1] Sorby, Presidential Address; *Q. J. G. S.* 1879; G. Rose, *Abhandl. Acad. Berlin*, 1858; Gümbel, *Z. D. G. G.* 1884, p. 386; Cornish and Kendall, *Geol. Mag.* 1888, p. 66; and the work of Dr. Cayeux already cited.

many cases, however, the decomposition products are so indefinite in form and so minute in quantity, as not to permit them to be satisfactorily referred to any known species of mineral. For these indeterminate, but frequently abundant substances, the following short names were proposed by Vogelsang to save periphrasis, until the true nature of the substance is ascertained. *Viridite*—green transparent or translucent patches, often in scaly or fibrous aggregations, of common occurrence in more or less decomposed rocks containing hornblende, augite, or olivine: probably in many cases serpentine, in others chlorite or delessite. *Ferrite*—yellowish, reddish or brownish amorphous substances, probably consisting of peroxide of iron, either hydrous or anhydrous, but not certainly referable to any mineral, though sometimes pseudomorphous after ferruginous minerals. *Opacite*—black, opaque grains and scales of amorphous earthy matter, which may in different cases be magnetite, or some other metallic oxide, earthy silicates, graphite, &c.[1]

### Sect. vi.—Classification of Rocks.

It is evident that the study of rocks may be approached from two very different sides. We may, on the one hand, regard these substances chiefly as so many masses of mineral matter, presenting great variety of chemical composition and marvellous diversity of microscopic structure. Or, on the other hand, passing from the details of their chemical and mineralogical characters, we may look at them rather as the records of ancient terrestrial changes. In the former aspect, they present for consideration problems of the highest interest in inorganic chemistry and mineralogy; in the latter view, they invite attention to the great geological revolutions through which the planet has passed. It is evident, therefore, that two distinct systems of classification might be followed, the one based on chemical and mineralogical, the other on geological considerations. It is impossible, however, in any system to ignore the fundamental twofold series in which the rocks of the terrestrial crust naturally group themselves. As geological action proceeds from two distinct sources, one derived from the internal energy of the planet itself, the other arising chiefly from the influence of the sun on the external surface of the planet, so it is obvious that the masses of mineral matter resulting from the operation of these two causes must be distinguished from each other in any scheme of classification, apart altogether from questions of structure or composition. In actual fact, however, it is found that the contrasted mode of origin is in each case accompanied by distinctions of structure and arrangement as well as mineralogical and chemical constitution. By general agreement, therefore, it is acknowledged that the first fundamental step in the classification of rocks must be a primary separation of them into two great divisions:—1st, Those which have accumulated on or near the surface of the earth through the operation of water, air or organic life. In this subdivision are included all accumulations of mechanical detritus, either organic or inorganic, under water or on land; of

[1] Vogelsang, *Z. D. G. G.* xxiv. (1872), p. 529. Zirkel, *Geol. Expl. 40th Parallel*, vol. vi. p. 12.

chemical precipitates from aqueous solution; and of material aggregated by the growth of plants and animals. All these accumulations may be found associated with each other. They are mainly sediments, and are generally disposed in layers or strata piled one over another as they were laid down. This great series of rocks, mainly arising from geological operations that depend upon solar influences, are comprised under the term Sedimentary or Stratified. 2nd, Those which have arisen from the movements and uprise of the earth's own internal molten magma. These may have cooled and solidified deep beneath the surface, or may have made their way up to daylight and have been poured forth in volcanic eruptions. This clearly defined assemblage of rocks is known as Eruptive, Igneous, Massive or Unstratified.

So far there is practically no room for difference of opinion, and ever since the rise of geology into the place of a science the broad distinction here stated has been recognised. But further examination of the terrestrial crust discloses the presence of a third series, the origin of which is by no means so evident. Some of the rocks of this series possess characters that obviously connect them with igneous rocks, into which indeed they may be seen to graduate, while others as evidently pass into true sedimentary strata. They are distinguished, however, from the members of either of the two other series by the possession of characters which show that certainly in some, possibly in all, cases they have resulted from the alteration or *metamorphism* of older rocks, either igneous or aqueous. In their most typical forms they are marked by the peculiar crystalline structure termed *schistosity* or *foliation* (p. 134), where their mineral constituents are seen to have re-crystallised in lenticular laminæ or folia. Hence this third series of rocks has been separated from the others under the name of Metamorphic.

This fundamental classification of the rocks of the earth's crust into three great sections is based on geological considerations, and commends itself by its obvious agreement with the ascertained facts regarding the structure of that crust. When, however, we advance further and try to devise a natural and convenient scheme of arrangement for each of the three series, various systems of arrangement suggest themselves, each having its advantages and drawbacks. From a merely chemical point of view, rocks might be grouped according to their composition: as Oxides, exemplified by formations of quartz, hæmatite, or magnetite; Carbonates, including the limestones and clay-ironstones; Silicates, embracing the vast majority of rocks, whether composed of a single mineral, or of more than one; Phosphates, such as guano and the older bone-beds and coprolitic deposits. Each of these groups might obviously be further subdivided into sections, according to the predominant chemical constitutent. A classification of this kind, however, would pay little or no regard to the mode of origin or conditions of occurrence of the rocks, and would not be well suited for the purposes of the geologist.

Again, from the purely mineralogical side, rocks might be classified with reference to their prevailing mineral ingredient. Thus, such subdivisions as Calcareous rocks, Quartzose rocks, Orthoclase rocks, Plagio-

clase rocks, Pyroxenic rocks, Hornblendic rocks, &c., might be adopted: but such an arrangement, though on the whole less objectionable from the point of view of the geologist, would be more suited for the arrangement of hand-specimens in a museum than for the investigation of rocks *in situ*.

Though no classification which can at present be proposed is wholly satisfactory, one which shall do least violence, at once to geological and to chemical and mineralogical relationships, is to be preferred. That which is given in the following pages is in the nature of a compromise between the claims of the different sides of the subject, but the geological requirements have been allowed to preponderate. It is in the division of the Igneous rocks that opinions are most widely divergent regarding the best principle of classification to be followed. In the introduction to that division some account will be given of other schemes of arrangement than that adopted in the present text-book.

It must be kept in view that in the classification here selected, and in the detailed description of rocks now to be given, many questions regarding the origin, structure and decomposition of these mineral masses must necessarily be alluded to which cannot be fully dealt with in this part of the volume, but must be left for adequate treatment by themselves in later pages. The student, however, will probably recognise a distinct advantage in this unavoidable preliminary reference to them in connection with the rocks by which they are suggested.

## Sect. vii.—A Description of the more Important Rocks of the Earth's Crust.

Full details regarding the composition, microscopic structure and other characters of rocks must be sought in such general treatises as those already cited (p. 88), and in the special memoirs quoted on subsequent pages. The purposes of the present text-book will be served by a succinct account of the more common or important rocks which enter into the composition of the crust of the earth.

### I. SEDIMENTARY.

#### A. FRAGMENTAL (CLASTIC).

This great series embraces all rocks of a secondary or derivative origin; in other words, all that consist of materials which have previously existed on or beneath the surface of the earth in another form, and the accumulation and consolidation of which gives rise to new compounds. Some of these materials have been produced by the mechanical action of wind, as in the sand-hills of sea-coasts and inland deserts (Æolian rocks); others by the operation of moving water, as the gravel, sand and mud of shores and river-beds (Aqueous sedimentary rocks); others by the accumulation of the entire or fragmentary remains of once living plants and animals (Organically-formed rocks); while yet another series has arisen from the gathering together of the loose débris thrown out by volcanoes (Volcanic tuffs). It is evident that in dealing with these various detrital formations, the degree of consolidation is of secondary importance. The soft sand and mud of a modern lake-bottom

differ in no essential respect from indurated ancient lacustrine strata, and may tell their geological story equally well. No line is to be drawn between what is popularly termed "rock" and the loose, as yet uncompacted, débris out of which solid masses may eventually be formed. Hence, in a geological arrangement, the modern and the ancient, the loose and the compact, being one in structure and mode of formation, are all classed together under the common name of Rocks.

It will be observed that, in several directions, we are led by the fragmental rocks to crystalline stratified deposits, some of which have been deposited from chemical solution, while others have resulted from the gradual conversion of a detrital into a crystalline structure. Both series of deposits are accumulated simultaneously and are often interstratified. Calcareous rocks formed of organic remains (p. 176) exhibit very clearly this gradual internal change, which more or less effaces their detrital origin, and gives them such a crystalline character as to entitle them to be ranked among the crystalline limestones.[1]

### 1. **Gravel and Sand Rocks** (Psammites).

As the deposits included in this subdivision are produced by the disintegration and removal of rocks by the action of the atmosphere, rain, rivers, frost, the sea and other superficial agencies, they are mere mechanical accumulations, and necessarily vary indefinitely in composition, according to the nature of the sources from which they are derived. As a rule, they consist of the detritus of siliceous rocks, these being among the most durable materials. Quartz, in particular, enters largely into the composition of sandy and gravelly detritus. Fragmentary materials tend to group themselves according to their size and relative density. Hence they are apt to occur in layers, and to show the characteristic *stratified* arrangement of *sedimentary* rocks. They may enclose the remains of any plants or animals entombed on the same sea-floor, river-bed or lake-bottom.

In the majority of these rocks, their general mineral composition is obvious to the naked eye. But the application of the microscope to their investigation has thrown considerable light upon their composition, formation and subsequent mutations. Their component materials are thus ascertained to be divisible into—1st, derived fragments, of which the most abundant are quartz, after which come felspar, mica, iron-ores, zircon, rutile, apatite, tourmaline, garnet, sphene, augite, hornblende, fragments of various rocks, and clastic dust; 2nd, constituents which have been deposited between the particles, and which in many cases serve as the cementing material of the rock. Among the more important of these are silicic acid in the form of quartz, chalcedony and opal; carbonates of lime, iron or magnesia; hæmatite, limonite; pyrite and glauconite.[2]

**Cliff Débris, Moraine Stuff, Scree Material**—angular rubbish disengaged by frost and ordinary atmospheric waste from cliffs, crags and steep slopes. It slides down the declivities of hilly regions, and accumulates at their base, until washed away by rain or by brooks. It forms talus-slopes, or what are known in England as *screes*, that may

[1] The most valuable series of modern chemical analyses of sedimentary rocks will be found in Mr. F. W. Clarke's Report in the *168th Bulletin of the United States Geological Survey* (1900), from which frequent citations will be made in the succeeding pages. For the microscopic characters of these rocks the work of Cayeux, cited *ante*, p. 106, may be consulted; also the 'Album de Microphotographies des Roches sédimentaires,' by Maurice Hovelacque, 4to, Paris, 1900.

[2] G. Klemm, *Z. D. G. G.* xxxiv. (1882), p. 771. H. C. Sorby, *Q. J. G. S.* xxxvi. (1880). J. A. Phillips, *op. cit.* xxxvii. (1881), p. 6.

have an inclination of as much as 40°, though for short distances, if the blocks are large, the general angle of slope may be steeper. It naturally depends for its composition upon the nature of the solid rocks from which it is derived. Where cliff-débris falls upon and is borne along by glaciers it is called "Moraine-stuff," which may be deposited near its source, or may be transported for many miles on the surface of the ice (p. 544).

**Perched Blocks, Erratic Blocks**—large masses of rock, often as big as a house, which have been transported by glacier-ice, and have been lodged in a prominent position in glacier valleys or have been scattered over hills and plains. An examination of their mineralogical character leads to the identification of their source and, consequently, to the path taken by the transporting ice. (See Book III. Part II. Sect. ii. § 5.)

**Rain-wash**—a loam or earth which accumulates on the lower parts of slopes or at their base, and is due to the gradual descent of the finer particles of disintegrated rocks by the transporting action of rain. Brick-earth is the name given in the south-east of England to thick masses of such loam, which is extensively used for making bricks.

**Soil**—the product of the subaerial decomposition of rocks and of the decay of plants and animals. Primarily the character of the soil is determined by that of the subsoil, of which indeed it is merely a further disintegration. According to the nature of the rock underneath, a soil may vary from a stiff clay, through various clayey and sandy loams, to mere sand. The formation of soil is treated of in Book III. Part II. Sect. ii. § i. As an example of the detailed investigation of the soils of a country, reference may be made to the elaborate description of those of Russia prepared by Professor Sibirtzew.[1] He distinguishes the loose or Æolian soils, those of the dry steppes or steppe-deserts, the Tchernozoms, the soils of the wooded steppes, the grassy soils, and those of the Tundras. In each of these he enumerates a series of genetic types, such as clay-soils, heavy and intermediate sub-argillaceous soils, light sub-argillaceous soils, sub-arenaceous soils, and clayey sands.

**Subsoil**—the broken-up part of the rocks immediately under the soil. Its character, of course, is determined by that of the rock out of which it is formed by subaerial disintegration. (Book III. Part II. Sect. ii. § 1.)

**Blown Sand**—loose sand usually arranged in lines of dunes, fronting a sandy beach or in the arid interior of a continent. It is piled up by the driving action of wind. (Book III. Part. II. Sect. i.) It varies in composition, being sometimes entirely siliceous, as upon shores where siliceous rocks are exposed ; sometimes calcareous, where derived from triturated shells, nullipores, or other calcareous organisms. The minute grains from long-continued mutual friction assume remarkably rounded and polished forms. Layers of finer and coarser particles often alternate, as in water-formed sandstone. On many coast-lines in Europe, grasses and other plants bind the surface of the shifting sand. These layers of vegetation are apt to be covered by fresh encroachments of the loose material, and then by their decay to give rise to dark peaty seams in the sand. Calcareous blown sand is compacted into hard stone by the action of rain-water, which alternately dissolves a little of the lime, and re-deposits it on evaporation as a thin crust cementing the grains of sand together. In the Bahamas and Bermudas, extensive masses of calcareous blown sand have been cemented in this way into solid stone, which weathers into picturesque crags and caves like a limestone of older geological date.[2] At Newquay, Cornwall, blown sand has, by the decay of abundant land-shells, been solidified into a material capable of being used as a building-stone.

[1] *Compt. rend. Congrès Géol. Internat.*, St. Petersburg, 1899, pp. 73-125.

[2] For interesting accounts of the Æolian deposits of the Bahamas and Bermudas, see Nelson, *Q. J. G. S.* ix. p. 200; Sir Wyville Thomson's 'Atlantic,' vol. i.; also J. J. Rein, *Senckenb. Nat. Gesellsch. Bericht.* 1869-70, p. 140, 1872-73, p. 131. On the Red Sands of the Arabian Desert, see J. A. Phillips, *Q. J. G. S.* xxxviii. (1882), p. 110; also *op. cit.* xxxvii. (1881), p. 12. Further reference to the literature of this subject will be found in the account of the effects of wind-action, *postea*, Book III. Part II. Sect. i. § 1.

**River-sand, Sea-sand.**—When the rounded water-worn detritus is finer than that to which the term gravel would be applied, it is called sand, though there is obviously no line to be drawn between the two kinds of deposit, which necessarily graduate into each other. The particles of sand range down to such minute forms as can only be distinctly discerned with a microscope. The smaller forms are generally less well rounded than those of greater dimensions, no doubt because their diminutive size allows them to remain suspended in agitated water; and thus to escape the mutual attrition to which the larger and heavier grains are exposed upon the bottom. (Book III. Part II. p. 496.) So far as experience has yet gone, there is no reliable method by which inorganic sea-sand can be distinguished from that of rivers or lakes.[1] As a rule, sand consists largely (often wholly) of quartz-grains. The presence of fragments of marine shells will of course betray its salt-water origin; but in the trituration to which sand is exposed on a coast-line, the shell-fragments are in great measure ground into calcareous mud and removed.[2]

Mr. Sorby has shown that, by microscopic investigation, much information may be obtained regarding the history and source of sedimentary materials. He has studied the minute structure of modern sand, and finds that sand-grains present the following five distinct types, which, however, graduate into each other:—

1. Normal, angular, fresh-formed sand, such as has been derived almost directly from the breaking up of granitic or schistose rocks.
2. Well-worn sand in rounded grains, the original angles being completely lost, and the surfaces looking like fine ground glass.
3. Sand mechanically broken into sharp angular chips, showing a glassy fracture.
4. Sand having the grains chemically corroded, so as to produce a peculiar texture of the surface, differing from that of worn grains or crystals.
5. Sand in which the grains have a perfectly crystalline outline, in some cases undoubtedly due to the deposition of quartz upon rounded or angular nuclei of ordinary non-crystalline sand.[3]

The same acute observer points out that, as in the familiar case of conglomerate pebbles, which have sometimes been used over again in conglomerates of very different ages, so with the much more minute grains of sand, we must distinguish between the age of the grains and the age of the deposit formed of them. An ancient sandstone may consist of grains that had hardly been worn before they were finally brought to rest, while the sand of a modern beach may have been ground down by the waves of many successive geological periods.

Sand taken by Mr. Sorby from the old gravel terraces of the River Tay was found to be almost wholly angular, indicating how little wear and tear there may be among particles of quartz $\frac{1}{100}$th of an inch in diameter, even though exposed to the drifting action of a rapid river.[4] Sand from the boulder clay at Scarborough was likewise ascertained to be almost entirely fresh and angular. On the other hand, in geological formations, which can be traced in a given direction for several hundred miles, a progressively large proportion of rounded particles may be detected in the sandy beds, as Mr. Sorby has found in following the Greensand from Devonshire to Kent. In wind-blown sand exposed for a long period to drift to and fro along the surface, the larger particles and pebbles acquire the remarkably smoothed and polished surface already (p. 161) referred to.

[1] See, however, on the general question of the investigation of sand, a paper by J. W. Retgers, "Über die mineralogische und chemische Zusammensetzung der Dünensande Hollands, und über die Wichtigkeit von Fluss- und Meeres-sanduntersuchungen in Allgemeinen," *Neues Jahrb.* 1895, i. pp.16-74.

[2] Professor Herdman has described the sandy and other deposits which are at present accumulating on the floor of the Irish Sea. *Brit. Assoc.* 1886, pp. 601-621.

[3] Address, *Q. J. G. S.* xxxvi. (1880), p. 58; and *Microscop. Journ.* Anniv. Address, 1877.

[4] See Book III. Part II. Sect. ii. § iii.

The occurrence of various other minerals besides quartz in ordinary sand has long been recognised, but we owe to the observations of Mr. A. B. Dick the discovery that among these minerals some of the most plentiful and most perfectly preserved belong to species that were not supposed to be so widely diffused, such as zircon, rutile and tourmaline. He has found that these heavy minerals constitute sometimes as much as 4 per cent of the Bagshot sand of the older Tertiary series of the London basin.[1] Felspars, micas, hornblendes, pyroxenes, magnetite, glauconite and other minerals may likewise be recognised. The remarkable perfection of some of the crystallographic forms of the minuter mineral constituents of certain sands has been well shown by Mr. Dick.

Varieties of river- or sea-sand may be distinguished by names referring to some remarkable constituent, *e.g.* magnetic sand, iron-sand, gold-sand, auriferous sand, &c.

**Gravel, Shingle**—names applied to the coarser kinds of rounded water-worn detritus. In Gravel, the average size of the component pebbles ranges from that of a small pea up to about that of a walnut, though of course many included fragments will be observed which exceed these limits. In Shingle, the stones are coarser, ranging up to blocks as big as a man's head or larger. German geologists distinguish as "schotter" a shingle containing dispersed boulders, and "schotter-conglomerate" a rock wherein these materials have become consolidated.[2] All these names are applied quite irrespective of the composition of the fragments, which varies greatly from point to point. As a rule, the stones consist of hard rocks, since these are best fitted to withstand the powerful grinding action to which they are exposed.

**Conglomerate** (Puddingstone)—a rock formed of consolidated gravel or shingle.[3] The component pebbles are rounded and water-worn. They may consist of any kind of rock, though usually of some hard and durable sort, such as quartz or quartzite. A special name may be given to the rock, according to the nature of its pebbles, as quartz-conglomerate, limestone-conglomerate, granite-conglomerate, &c., or according to that of the paste or cementing matrix, which may consist of a hardened sand or clay, and may be siliceous, calcareous, argillaceous or ferruginous. In the coarser conglomerates, where the blocks may exceed six feet in length, there is often very little indication of stratification. Except where the flatter stones show by their general parallelism the rude lines of deposit, it may be only when the mass of conglomerate is taken as a whole, in its relation to the rocks below and above it, that its claim to be considered a bedded rock will be conceded. The occurrence of occasional bands of conglomerate in a series of arenaceous strata is analogous probably to that of a shingle-bank or gravel-beach on a modern coast-line. But it is not easy to understand the circumstances under which some ancient conglomerates accumulated, such as that of the Old Red Sandstone of Central Scotland, which attains a thickness of many thousand feet, and consists of well-rounded and smoothed blocks often several feet in diameter.

In many old conglomerates (and even in those of Miocene age in Switzerland) the component pebbles may be observed to have indented each other. In such cases also they may be found elongated, distorted or split and re-cemented; sometimes the same pebble has been crushed into a number of pieces, which are held together by a retaining cement. These phenomena point to great pressure, and some internal relative movement in the rocks. (Book III. Part I. Sect. iv. § 3.) Other indications of great disturbance are mentioned in the following description of Breccia.

**Breccia**—a rock composed of angular, instead of rounded, fragments. It commonly

[1] *Nature*, xxxvi. (1877), p. 91; *Mem. Geol. Surv.* "Geology of London," i. (1889), p. 523. Teall, 'British Petrography,' Plate xliv.

[2] See, for example, an account of the schotter-conglomerates of Northern Persia by E. Tietze, *Jahrb. Geol. Reichsanst.*, Vienna, 1881, p. 68.

[3] See A. Helland, "Studier over Konglomerater," *Archiv. Mathem. Naturvidens.*, Christiania, 1880.

presents less trace of stratification than conglomerate. Intermediate stages between these two rocks, where the stones are partly angular and partly subangular and rounded, are known as *brecciated conglomerate.* Considered as a detrital deposit formed by superficial waste, breccia points to the disintegration of rocks by the atmosphere, and the accumulation of their fragments with little or no intervention of running water. Thus it may be formed of cliff-débris or scree-material which gradually slides down a slope below a crag or cliff, or which may be launched forward by a landslip and may accumulate either subaerially, or under water where the cliff descends at once into a lake or into the deep sea.

The term Breccia has, however, been applied to rocks formed in several other totally different ways. Angular blocks of all sizes and shapes have been discharged from volcanic orifices, and, falling back, have consolidated there into masses of brecciated material (volcanic breccia). Intrusive igneous eruptions have sometimes torn off fragments of the rocks through which they have ascended, and these angular fragments have been enclosed in the liquid or pasty mass. Or the intrusive rock has cooled and solidified externally while still mobile within, and in its ascent has caught up and involved some of these consolidated parts of its own substance. Again, where solid masses of rock within the crust of the earth have ground against each other, as in dislocations and crushing movements, angular fragmentary rubbish has been produced, which has subsequently been consolidated by some infiltrating cement (Fault-rock, Crush-breccia, Crush-conglomerate). It is evident, however, that breccia formed in one or other of these hypogene ways will not, as a rule, be apt to be mistaken for the true breccias, arising from superficial disintegration.

**Sandstone** (Grès)[1]—a rock composed of consolidated sand. As in ordinary modern sand, the integral grains of sandstone are chiefly quartz, which must here be regarded as the residue left after all the less durable minerals of the original rocks have been carried away in solution or in suspension as fine mud. The colours of sandstones arise, not so much from that of the quartz, which is commonly white or grey, as from the film or crust which often coats the grains and holds them together as a cement. Iron, the great colouring ingredient of rocks, gives rise to red, brown, yellow, and green hues, according to its degree of oxidation and hydration.

Like conglomerates, sandstones differ in the nature of their component grains, and in that of the cementing matrix. Though consisting for the most part of siliceous grains, they include others of clay, felspar, mica, zircon, rutile, tourmaline or other minerals such as occur in sand (p. 163), and these may increase in number so as to give a special character to the rock. Thus, sandstones may be argillaceous, felspathic, micaceous, calcareous, &c. By an increase in the argillaceous constituents, a sandstone may pass into one of the clay-rocks, just as modern sand on the sea-floor shades imperceptibly into mud. On the other hand, by an augmentation in the size and sharpness of the grains, a sandstone may become a grit, and by an increase in the size and number of pebbles may pass into a pebbly or conglomeratic sandstone, and thence into a fine conglomerate. A piece of fine-grained sandstone, seen under the microscope, looks like a coarse conglomerate, so that the difference between the two rocks is little more than one of relative size of particles.

The cementing material of sandstones may be *ferruginous*, as in most ordinary red and yellow sandstones, where the anhydrous or hydrous iron-oxide is mixed with clay or other impurity—in red sandstones the grains are held together by a hæmatitic, in yellow sandstones by a limonitic cement; *argillaceous*, where the grains are united by a base of clay, recognisable by the earthy smell when breathed upon; *calcareous*, where carbonate of lime occurs either as an amorphous paste or as a crystalline cement

[1] See J. A. Phillips on the constitution and history of grits and sandstones, *Q. J. G. S.* xxxvii. (1881), p. 6. For analyses of some British sandstones used as building-stones, see Wallace, *Proc. Phil. Soc. Glasgow*, xiv. (1883), p. 22.

between the grains; *siliceous*, where the component particles are bound together by silica, as in the exposed blocks of Eocene sandstone known as "greyweathers" in Wiltshire, and which occur also over the north of France towards the Ardennes.[1] In some places, as already remarked (p. 107), barytes has supplied the place of cement to the grains of sandstone.

The following analyses show the average chemical composition of sandstones and the great range in their silica percentage. Column A represents the results of a composite analysis of 253 sandstones from different parts of the United States, and column B of 371 sandstones used for building purposes in different parts of the same country. Column C shows the extraordinarily high proportion of silica in the highly quartzose Potsdam sandstone, which forms one of the prominent formations among the older Palæozoic rocks of Canada and adjoining parts of the States. Column D represents the composition of a calcareous and argillaceous sandstone from the Miocene formations of Wall Point, Mount Diablo, California.[2]

| | A | B | C | D |
|---|---|---|---|---|
| $SiO_2$ | 78·66 | 84·86 | 99·42 | 44·54 |
| $T_1O_2$ | 0·25 | 0·41 | ... | ... |
| $Al_2O_3$ | 4·78 | 5·96 } | 0·31 | 12·63 |
| $Fe_2O_3$ | 1·08 | 1·39 } | | 2·50 |
| FeO | 0·30 | 0·84 | ... | 3·08 |
| MnO | trace | trace | ... | 0·44 |
| CaO | 5·52 | 1·05 | ... | 14·65 |
| SrO | trace | none | ... | ... |
| BaO | 0·05 | 0·01 | ... | ... |
| MgO | 1·17 | 0·52 | ... | 5·55 |
| $K_2O$ | 1·32 | 1·16 | ... | 1·37 |
| $Na_2O$ | 0·45 | 0·76 | ... | 3·35 |
| $Li_2O$ | trace | trace | ... | ... |
| $H_2O$ at 110° | 0·31 | 0·27[3] } | 0·18 | 1·43 |
| $H_2O$ above 110° | 1·33[3] | 1·47 } | | 2·25 |
| $P_2O_5$ | 0·08 | 0·06 | ... | 0·29 |
| $CO_2$ | 5·04 | 1·01 | ... | 7·76 |
| $SO_3$ | 0·07 | 0·09 | ... | ... |
| Cl | trace | trace | ... | ... |
| | 100·41 | 99·86 | 99·91 | 99·84 |

Among the varieties of sandstone the following may here be mentioned:—Flagstone—a thin-bedded sandstone, capable of being split along the lines of stratification into thin beds or flags; Micaceous sandstone (*mica-psammite*)—a rock so full of mica-flakes that it splits readily into thin laminæ, each of which has a lustrous surface from the quantity of silvery mica. This rock is called "fakes" in Scotland. Freestone—a sandstone (the term being applied sometimes also to limestone) which can be cut into blocks in any direction, without a marked tendency to split in any one plane more than in another. Though this rock occurs in beds, each bed is not divided into laminæ, and it is the absence of this minor stratification which makes the stone so useful for architectural purposes (Craigleith and other sandstones at Edinburgh, some of which

[1] See the original description of these French blocks by Professor Barrois, *Ann. Soc. Géol. Nord.* vi. (1878-79), p. 366.

[2] *Bull. U. S. G. S.* No. 168 (1900), pp. 17, 245, 249. The analyses in columns A and B were made by Dr. H. N. Stokes, that in column C by Mr. Schneider, and that in column D by Mr. W. H. Melville.

[3] Includes organic matter.

contain 98 per cent of silica). Glauconitic sandstone (greensand)—a sandstone containing kernels and dusty grains of glauconite, which imparts a general greenish hue to the rock. The glauconite has probably been deposited in association with decaying organic matter, as where it fills echinus-spines, foraminifera, shells and corals on the floor of the present ocean.[1] Buhrstone—a highly siliceous, exceedingly compact, though cellular rock (with *Chara* seeds, &c.), found alternating with unaltered Tertiary strata in the Paris basin, and forming, from its hardness and roughness, an excellent material for the grindstones of flour-mills, may be mentioned here, though it probably has been formed by the precipitation of silica through the action of organisms. Gaize —a fine-grained, sandy, siliceous, porous, and often rather tender rock, found in the Cretaceous and Tertiary formations of France, distinguished by its containing silica soluble in alkalies.[2] Arkose (*granitic sandstone*)—a rock composed of disintegrated granite, and found in geological formations of different ages, which have been derived from granitic rocks. Crystallised sandstone—an arenaceous rock in which a deposit of crystalline quartz has taken place upon the individual grains, each of which becomes the nucleus of a more or less perfect quartz crystal. Mr. Sorby has observed such crystallised sand in deposits of various ages from the Oolites down to the Old Red Sandstone.[3] Tuffeau—a name employed in France and Belgium for a fine-grained argillaceous, frequently calcareous sandstone, coloured green or grey by glauconite ; it is sometimes applied to a friable granular chalky limestone.[4] (For Quartzite, see p. 249.)

Sandstones are largely employed for building purposes on account of their durability and the facility with which they can be worked. Hence a large amount of information has been collected as to their composition, specific gravity, crushing strength, capacity for absorbing water, and other practical matters connected with their use. Information on these subjects will be found in the works of Mr. G. P. Merrill, mentioned *ante*, p. 7.

**Greywacke**—a compact aggregate of rounded or subangular grains of quartz, felspar. slate, or other minerals or rocks, cemented by a paste which is usually siliceous, but may be argillaceous, felspathic, calcareous, or anthracitic (Fig. 20). Grey, as its name denotes, is the prevailing colour : but it passes into brown, brownish-purple, and sometimes, where anthracite predominates, into black. The rock is distinguished from ordinary sandstone by its darker hue, its hardness, the variety of its component grains, and, above all, by the compact cement in which the grains are imbedded. In many varieties, so pervaded is the rock by the siliceous paste, that it possesses great toughness, and its grains seem to graduate into each other as well as into the surrounding matrix. Such rocks, when fine-grained, can hardly, at first sight or with the unaided eye, be distinguished from some compact igneous rocks, though microscopic examination reveals their fragmental character. In other cases, where the greywacke has been formed mainly out of the débris of granite, quartz-porphyry, andesite, or other felspathic masses, the grains consist so largely of felspar, and the paste also is so felspathic, that the rock might be mistaken for some close-grained granular porphyry. Greywacke occurs extensively among the Palæozoic formations, in beds alternating with shales and conglomerates. It represents the muddy (sometimes volcanic) sand of Palæozoic sea-floors,

[1] *Ante*, p. 106 ; Sollas, *Geol. Mag.* iii. 2nd ser. p. 539. L. Cayeux, *Étude microg. Terr. sédim.* chap. iv.

[2] Cayeux, *op. cit.* chap. i. A specimen of the Gaize of Marlemont analysed at the École des Mines gave the following composition : silica soluble in potash, 20·6 ; insoluble silica, 68·4 ; alumina, 1 ; ferric oxide, 3·0 ; lime, 1·3 ; loss by calcination, 5·6 ; total, 99·9. Cayeux, *op. cit.* p. 41.

[3] *Q. J. G. S.* xxxvi. p. 63. See Daubrée, *Ann. des Mines*, 2nd ser. i. p. 206. A. A. Young, *Amer. Journ. Sci.* 3rd ser. xxiii. 257 ; xxiv. 47 ; and especially the work of Irving and Van Hise (quoted on p. 142), which gives some excellent figures of enlarged quartz-grains. S. Calvin, *Amer. Geol.* xiii. (1894) p. 225, also gives good figures.

[4] L. Cayeux, *Microg. Terr. sédim.* chap. iii.

retaining often its ripple-marks and sun-cracks. The metamorphism it has undergone has generally not been great, and for the most part is limited to induration, partly by pressure and partly by permeation of a siliceous cement. But where felspathic ingredients prevail, the rock has offered facilities for alteration, and has been here and there changed into highly crystalline mica-schists full of garnets and other secondary minerals (contact-metamorphism at the granite of South-western Scotland, *postea*, p. 779).

The following analysis gives the composition of a greywacke from Hurley, Wisconsin: silica, 76·84; alumina, 11·76; ferric oxide, 0·55; ferrous oxide, 2·8; magnesia, 1·39; lime, 0·70; soda, 2·57; potash, 1·62; water, 1·87; manganese, a trace—total, 100·18.[1]

The more fissile fine-grained varieties of this rock have been termed **Greywacke-slate** (p. 172). In these, as well as in greywacke, organic remains occur among the Silurian and Devonian formations. Sometimes, in the Lower Silurian rocks of Scotland, these strata become black with carbonaceous matter, among which vast numbers of graptolites may be observed. Gradations into sandstone are termed **Greywacke-sandstone**. In Norway the reddish felspathic greywacke or sandstone of the Primordial rocks is called **Sparagmite**; similar material, graduating into arkose, forms much of the Torridon sandstone of Scotland.

Besides these rocks, which are obviously of clastic origin, there may be included here some others of a highly siliceous nature, but the sedimentary character and mode of formation of which are not so clear. Such are **Jasper**, and **Ferruginous Quartz**, which occur in beds interstratified among some older Palæozoic and pre-Cambrian formations, as well as in veins together with vein-quartz. With them may be grouped **Lydian-stone** (*Lydite, Phthanite, Kieselschiefer*), a black or dark-coloured, excessively compact, hard, infusible rock with splintery fracture, occurring in thin, sharply defined bands, split by cross joints into polygonal fragments, which are sometimes cemented by fine layers of quartz. It consists of an intimate mixture of silica with alumina, carbonaceous materials, and oxide of iron, and under the microscope shows minute quartz-granules with dark amorphous matter. It occurs in thin layers or bands in the Silurian and later Palæozoic formations interstratified with ordinary sandy and argillaceous strata. As these rocks have not been materially altered, the bands of Lydian-stone may be of original formation, though the extent to which they are often veined with quartz shows that they have, in many cases, been permeated by siliceous water since their deposit. Some originally clastic siliceous rocks have acquired a more or less crystalline structure from the action of thermal water or otherwise. One of the most marked varieties, *Crystallised Sandstone*, has been above referred to. Another variety, known as *Quartzite*, is a granular and compact aggregate of quartz, which will be described in connection with the schistose rocks among which it generally occurs (p. 249). The siliceous rocks due to the operations of plant and animal life are described on p. 179, also on pp. 609, 624.

## 2. **Clay Rocks** (Pelites).

These are composed of fine argillaceous sediment or mud, derived from the waste of rocks. Perfectly pure clay or kaolin, hydrated silicate of alumina, may be obtained where granites and other felspar-bearing rocks decompose. But, as a rule, the argillaceous materials are mixed with various impurities.[2]

[1] Described by Mr. W. S. Bayley (who gives an account of its microscopic character), and analysed by Dr. H. N. Stokes, *Bull. U. S. G. S.* No. 150, pp. 84, 87.

[2] The literature connected with clays, especially in their industrial application, has been catalogued by Mr. J. C. Branner, "Bibliography of Clays and the Ceramic Arts," *Bull. U. S. G. S.* No. 143 (1896). An important investigation in the subject by Dr. H. Ries will be found in the "Preliminary Report on the Clays of Alabama," in *Bull. No. 6, Geol. Surv. Alabama* (1900); also *Trans. Amer. Inst. Min. Engin.* February 1898. The

**Clay, Mud** (Argile, Boue; Thon, Schlamm).—The decomposition of felspars and allied minerals gives rise to the formation of hydrous aluminous silicates, which, occurring usually in a state of fine subdivision, are capable of being held in suspension in water, and of being transported to great distances. These substances, differing much in composition, are embraced under the general term Clay, which may be defined as a white, grey, brown, red, or bluish substance, which when dry is soft and friable, adheres to the tongue, and shaken in water makes it mechanically turbid; when moist is plastic, when mixed with much water becomes mud.[1] It is evident that a wide range is possible for varieties of argillaceous sediment. The following are the more important.

**Kaolin** (Porcelain-clay, China-clay) has been already noticed (p. 104).

**Pipe-Clay**—white, nearly pure, and free from iron.

**Fire-Clay**—largely found in connection with coal-seams, contains little iron, and is nearly free from lime and alkalies. It has been derived from the waste of such rocks as granite.[2] Some of the most typical fire-clays are those long used at Stourbridge, Worcestershire, for the manufacture of pottery. The best glass-house pot-clay, that is, the most refractory, and therefore used for the construction of pots which have to stand the intense heat of a glass-house, has the following composition: silica, 73·82; alumina, 15·88; protoxide of iron, 2·95; lime, trace; magnesia, trace; alkalies, ·90; sulphuric acid, trace; chlorine, trace; water, 6·45; specific gravity, 2·51.

**Gannister**—a very siliceous close-grained variety, found in the Lower Coal-measures of the north of England, and now largely ground down as a material for the hearths of iron furnaces.

**Brick-clay**—properly rather an industrial than a geological term, since it is applied to any clay, loam, or earth from which bricks or coarse pottery are made. It is an impure clay, containing a good deal of iron, with other ingredients. An analysis gave the following composition of a brick-clay: silica, 49·44; alumina, 34·26; sesquioxide of iron, 7·74; lime, 1·48; magnesia, 5·14; water, 1·94.

**Abysmal Clay**—on the ocean-floor at great depths certain red clays have a wide distribution. They are described at p. 583.

**Fuller's Earth** (Terre à foulon, Walkerde)—a greenish or brownish, earthy, soft, somewhat unctuous substance, with a shining streak, which does not become plastic with water, but crumbles down into mud. It is a hydrous aluminous silicate with some magnesia, iron-oxide and soda. The yellow fuller's-earth of Reigate contains silica 53, alumina 10, oxide of iron 9·75, magnesia 1·25, lime 0·50, chloride of sodium 0·10, water 24; total, 98·60.[3] In England fuller's-earth occurs in beds among the Jurassic and Cretaceous formations. In Saxony it is found as a result of the decomposition of diabase and gabbro.

**Wacke**—a dirty-green to brownish-black, earthy or compact, but tender and apparently homogeneous clay, which arises as the ultimate stage of the decomposition of basalt-rocks *in situ*.

**Loam**—an earthy mixture of clay and sand with more or less organic matter. The

minute structures of modern clays and old allied rocks are well discussed by Mr. Hutchings in a series of papers in the *Geol. Mag.* 1894, p. 36, and 1896, pp. 309, 343. He shows how fine sedimentary material may be best studied, whether loose or in solid rock. Professor Sollas has described the mud of the Severn and its tributaries, *Q. J. G. S.* xxxix. (1883), pp. 611-625.

[1] A series of chemical analyses of clays and soils will be found in *Bull. U. S. G. S.* No. 168 (1900). In these the proportion of alumina ranges from less than 1 up to more than 39 per cent, whence it will be seen what a wide range of composition is embraced in the mechanical sediments which are all loosely described as clays.

[2] For an account of a microscopic study of the composition and structure of fire-clay see Mr. Hutchings' papers, above cited.

[3] Klaproth, *Beiträge*, iv. p. 334.

black soils of Russia, India, &c. (Tchernozom, Regur), are dark deposits of loam rich in organic matter, and sometimes upwards of twenty feet deep. (See Book III. Part. II. pp. 605, 606.)

**Loess**—a pale, somewhat calcareous clay, probably in large measure of wind-drift origin, found in some river-valleys (Rhine, Danube, Mississippi, &c.), and over wide regions in China and elsewhere. It is described at p. 439.

**Bauxite**—a hydrated alumina recognised first at Baux near Arles, in the south of France. It is seldom pure, but occurs mingled with clay, iron and other impurities in variable proportions in layers and beds, sometimes of considerable extent. It contains from 45 to nearly 80 per cent of alumina, and about 15 per cent of water, with some ferric oxide, titanic acid and silica. Its mode of origin has been the subject of much discussion. Some observers have supposed it to have been formed by hydrothermal action, and its occasional pisolitic structure, as in Arkansas, has been cited in support of this view. The general tendency of opinion, however, is to regard the substance as mainly due to the subaerial action of acidulous waters on rocks containing aluminous silicates, such as granite, syenite, basalt or andesite. It is probably closely related to Laterite, like which it varies much in composition and in the proportion of iron it contains. Sometimes it passes laterally or vertically into earthy hæmatite, the oxides of iron and aluminium being liberated by the same process of decomposition among rocks containing these metals in the form of silicates. Bauxite occurs in the Departments of the Ariége and Herault in France, the Vogelsberg, the north of Ireland, and other parts of Europe, and in Arkansas, New Mexico, Alabama, and other districts of the United States. It is a valuable source for the manufacture of aluminium and alum, and being remarkably refractory has been employed for lining furnaces.[1]

**Laterite**—a cellular, reddish, ferruginous clay, found in some tropical countries as the result of the subaerial decomposition of certain kinds of rock, as granites, gneiss, diorite and basalt; it acquires great hardness after being quarried out and dried. The peculiar kind of alteration exemplified by this rock and by Bauxite has been termed "Laterisation."[2]

**Till, Boulder-clay**—a stiff sandy and stony clay, varying in colour and composition, according to the character of the rocks of the district in which it lies. It consists of "rock-flour," in other words, the material of many different kinds of rocks ground up by land-ice into the finest state of comminution.[3] It is usually full of worn stones of all sizes, up to blocks weighing several tons, and often well-smoothed and striated. It is a glacial deposit, and will be described among the formations of the Glacial Period.

**Mudstone**—a fine, usually more or less sandy, argillaceous rock, having no fissile character, and of somewhat greater hardness than any form of clay. The term Clayrock has been applied by some writers to an indurated clay that requires to be ground and mixed with water before it acquires plasticity.

**Shale** (Schiste, Schieferthon)—a general term to describe clay that has assumed a thinly stratified or fissile structure. Under this term are included laminated and somewhat hardened argillaceous rocks, which are capable of being split along the lines of

[1] A somewhat voluminous bibliography has arisen on the subject of bauxite. The following papers may be cited:—Daubrée, *B. S. G. F.* xxvi. (1869), p. 915; Coquand, *op. cit.* xxviii. (1870), p. 98; Dieulafait, *Compt. rend.* xciii. (1881), p. 804; A. von Liebrich, *Zeitsch. Kryst. Min.* xxiii. p. 296; *Ber. Oberhess. Ges. Nat. u. Heilkund.* xxviii. pp. 57-98; J. C. Branner, *Journ. Geol.* v. (1897), pp. 263-289j. (this paper contains a good bibliography); C. W. Hayes, *16th Ann. Rep. U. S. G. S.* (1895), part iii. pp. 547-597; *21st Ann. Rep.* part iii. pp. 435-472; L. Watson, *Amer. Geol.* xxviii. (1901), p. 25.

[2] See M. Bauer, "Beiträge zur Geologie der Seychellen, insbesondere zur Kenntniss des Laterites," *Neues Jahrb.* 1898, ii. p. 168.

[3] Mr. Crosby, *Proc. Boston Nat. Hist. Soc.* xxv. (1890), pp. 115-172, has shown this clearly for the till around Boston, Mass.

deposit into thin leaves. It has been ascertained in many cases that the clay-substance in shales and slates is not mere impure kaolin, but has undergone alteration into a micaceous material, in which fine grains, probably detrital, are imbedded. When the sediment undergoes compression into slate the greenish-yellow mica becomes recognisably muscovite together with chloritic material. By further dynamical metamorphism the sediment passes into phyllite and mica-schist (p. 247). Shales present almost endless varieties of texture and composition, passing, on the one hand, into clays, or, where much indurated, into slates and argillaceous schists ; on the other, into flagstones and sandstones ; or again, through calcareous gradations into limestone, or through ferruginous varieties into clay-ironstone, and through bituminous kinds into coal. The average composition of a large series of Palæozoic, Secondary, and Tertiary shales, analysed by the United States Geological Survey, is shown in the subjoined table.[1]

| | A | B | C |
|---|---|---|---|
| $SiO_2$ | 55·43 | 60·15 | 58·38 |
| $TiO_2$ | 0·46 | 0·76 | 0·65 |
| $Al_2O_3$ | 13·84 | 16·45 | 15·47 |
| $Fe_2O_3$ | 4·00 | 4·04 | 4·03 |
| FeO | 1·74 | 2·90 | 2·46 |
| MnO | trace | trace | trace |
| CaO | 5·96 | 1·41 | 3·12 |
| BaO | 0·06 | 0·04 | 0·05 |
| Mg | 2·67 | 2·32 | 2·45 |
| $K_2O$ | 2·67 | 3·60 | 3·25 |
| $Na_2O$ | 1·80 | 1·01 | 1·31 |
| $Li_2O$ | trace | trace | trace |
| $H_2O$ at 110° | 2·11 | 0·89 | 1·34 |
| $H_2O$ above 110° | 3·45 | 3·82 | 3·68 |
| $P_2O_5$ | 0·20 | 0·15 | 0·17 |
| $CO_2$ | 4·62 | 1·46 | 2·64 |
| $SO_3$ | 0·78 | 0·58 | 0·65 |
| Carbon of organic origin | 0·69 | 0·88 | 0·81 |
| | 100·48 | 100·46 | 100·46 |

**Clay-Slate** (Schiste ardoise, Thonschiefer).—Under this name are included certain hard fissile argillaceous masses, composed primarily of compact clay, sometimes with megascopic and microscopic scales of one or more micaceous minerals, granules of quartz and cubes or concretions of pyrites, as well as veins of quartz and calcite. The fissile structure is specially characteristic. In some cases this structure coincides with that of original deposit, as is proved by the alternation of fissile beds with bands of hardened sandstone, conglomerate or fossiliferous limestone. But for the most part, as the rocks have been much compressed, the fissile structure of the argillaceous bands is independent of stratification, and can be seen traversing it. Sorby has shown that this superinduced fissility or "cleavage" has resulted from an internal rearrangement of the particles in planes perpendicular to the direction in which the rocks have been compressed (see *postea*, pp. 417 and 684). In England the term "slate" or "clay-slate" is given to

[1] Analyses by Dr. H. N. Stokes, *Bull. U. S. G. S.* No. 168 (1900), p. 17. Column A gives the composite analysis of 27 Mesozoic and Cenozoic shales. Each individual shale was taken in amount roughly proportional to the mass of the formation which it represented. Column B gives the composite analysis of 51 Palæozoic shales, weighted as in the former case. Column C shows the general average of A and B, giving them, respectively, weights as 3 to 5. This average represents 78 rocks. It should be added that the material was selected and the samples prepared by Mr. G. K. Gilbert, assisted by Mr. G. W. Stose.

argillaceous, not obviously crystalline rocks possessing this cleavage-structure. Where the micaceous lustre of the finely disseminated superinduced mica is prominent, the rocks become phyllites.

Microscopic examination shows that many cleaved clay-slates contain a large proportion of a micaceous mineral in extremely minute flakes, which in the best Welsh slates have an average size of $\frac{1}{2000}$th of an inch in breadth, and $\frac{1}{8000}$th of an inch in thickness, together with very fine black hairs which may be magnetite.[1] Moreover, many clay-slates, though to outward appearance thoroughly non-crystalline, and evidently of fragmental composition and sedimentary origin, yet contain, sometimes in remarkable abundance, microscopic microlites and crystals of different minerals placed with their long axes parallel with the planes of fissility. These minute bodies include yellowish-brown needles of rutile, greenish or yellowish flakes of mica, scales of calcite, and probably other minerals.[2] Small granules of quartz containing fluid-cavities, show on their surfaces a distinct blending with the substance of the surrounding rock. M. Renard has found that the Belgian whet-slate is full of minute crystals of garnet.[3] Some of the more crystalline varieties (phyllite) are almost wholly composed of minute crystalline particles of mica, quartz, felspar, chlorite and rutile, and form an intermediate stage between ordinary clay-slate and mica-schist.

A distinction has been drawn by some petrographers between certain rocks (phyllite, p. 247, Urthonschiefer) which occur in Archæan regions or in groups probably of high antiquity, and others (ardoise, Thonschiefer) which are found in Palæozoic and later formations. But there does not appear to be adequate justification for this grouping, which has probably been suggested rather by theoretical exigencies than by any essential differences between the rocks themselves. That the whole of the series of argillaceous rocks, beginning with clay and passing through shale into slate and phyllite, is of sedimentary origin is indicated by the organic remains, false bedding, ripple-mark, &c., found in those at one end of the series, and by the insensible gradation of the mineralogical characters through increasing stages of metamorphism to the other end. Some microscopic crystals may possibly have been originally formed among the muddy sediment on the sea-floor (see p. 585). Others may have formed part of the original mechanical detritus that went to make the slate. But, for the most part, they have been subsequently developed within the rock, and represent early stages of the process which has culminated in the production of crystalline schists. The development of crystals of chiastolite and other minerals in clay-slate is frequently to be observed round bosses of granite, as one of the phases of contact-metamorphism (see pp. 772-785).

A number of varieties of Clay-slate are recognised. Roofing slate (Dachschiefer) includes the finest, most compact, homogeneous and durable kinds, suitable for roofing houses or the manufacture of tables, chimney-pieces, writing-slates, &c. Anthracitic-slate (anthracite-phyllite, alum-slate), dark carbonaceous slate with much iron-disulphide. Bands of this nature sometimes run through a clay-slate region. The carbonaceous material arises from the alteration of the remains of plants (fucoids) or animals (frequently graptolites). The marcasite so abundantly associated with these organisms decomposes on exposure, and the sulphuric acid produced, uniting with the alumina,

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1 Sorby, *Q. J. G. S.* xxvi. p. 68.

2 These "clay-slate needles" may, in some cases, have been deposited with the rest of the sediment as part of the débris of pre-existing crystalline rocks (see p. 163); but in general they appear to have been developed where they now occur by subsequent actions (see *postea*, pp. 419, 773). For their character see Zirkel, 'Mik. Beschaff.' p. 490; Kalkowsky, *N. Jahrb.* 1879, p. 382; A. Cathrein, *op. cit.* i. (1882), p. 169; A. Penck, *Sitzb. Bayer. Akad. Math. Phys.* 1880, p. 461; A. Wichmann, *Q. J. G. S.* xxxv. p. 156; the papers by Mr. Hutchings cited on p. 168; Mr. A. R. Hunt, *Geol. Mag.* 1896, pp. 31, 79.

3 *Acad. Roy. Belgique*, xli. (1877). See also his papers on the composition and structure of the phyllades of the Ardennes, *Bull. Mus. Roy. Belg.* i. (1882): iii. (1884), p. 231.

potash, and other bases of the surrounding rocks, gives rise to an efflorescence of alum, or the decomposition produces sulphurous springs, like those of Moffat. As above stated, the name Greywacke-slate has been applied to extremely fine-grained, hard, shaly, more or less micaceous and sandy bands, associated with greywacke among the older Palæozoic rocks. Whet-slate, Novaculite, Hone-stone (Coticule, Wetzschiefer)[1] is an exceedingly hard fine-grained siliceous rock, some varieties of which derive their economic value from the presence of microscopic crystals of garnet. The various forms of altered clay-slate are described at p. 247 among the metamorphic rocks.

**Porcellanite** (Argillite)—a name applied to the exceedingly indurated, sometimes partially fused condition which shales are apt to assume in contact with dykes and intrusive sheets or bosses. For an account of this form of contact-metamorphism see p. 768. It is hardly possible to discriminate between such highly baked shales and some of the finer siliceous sediments which have been called Lydian-stone (p. 167).

### 3. Volcanic Fragmental Rocks—Tuffs.

This section comprises all deposits which have resulted from the comminution of volcanic rocks. They thus include (1) those which consist of the fragmentary materials ejected from volcanic foci, or the true ashes and tuffs; and (2) some rocks derived from the superficial disintegration of already erupted and consolidated volcanic masses. Obviously the second series ought properly to be classed with the sandy or clayey rocks above described, since they have been formed in the same way. In practice, however, these detrital reconstructed rocks cannot always be certainly distinguished from those which have been formed by the consolidation of true volcanic dust and sand. Their chemical and lithological characters, both megascopic and microscopic, are occasionally so similar, that their respective modes of origin have to be decided by other considerations, such as the occurrence of lapilli, bombs or slags in the truly volcanic series, and of well water-worn pebbles of volcanic rocks in the other. Attention to these features, however, usually enables the geologist to make the distinction, and to perceive that the number of instances where he may be in doubt is less than might be supposed. Only a comparatively small number of the rocks classed here are not true volcanic ejections.[2]

Referring to the account of volcanic action in Book III. Part I. Sect. i., we may here merely define the use of the names by which the different kinds of ejected volcanic materials are known.

**Volcanic Blocks**—angular, sub-angular, round, or irregularly shaped masses of lava, varying in size up to several feet or yards in diameter, sometimes of uniform texture throughout, as if they were large fragments dislodged by explosion from a previously consolidated rock, sometimes compact in the interior and cellular or slaggy outside.

**Bombs**—round, elliptical, or discoidal pieces of lava from a few inches up to one or more feet in diameter. They are frequently cellular internally, while the outer parts are fine-grained. Occasionally they consist of a mere shell of lava with a hollow interior like a bomb-shell, or of a casing of lava enclosing a fragment of rock. Their mode of origin is explained in Book III. Part I. Sect. i. § 1.

**Lapilli** (rapilli)—ejected fragments of lava, round, angular, or indefinite in shape, varying in size from a pea to a walnut. Their mineralogical composition depends upon

[1] This rock has given rise to much discussion and a variety of theories as to its origin. It has been claimed as having been a mechanical silt, an organic mud, a chemical precipitate, an igneous deposit, a replacement of original clay, a replacement of limestone, a replacement of dolomite. The bibliography of the subject is briefly given by Mr. J. C. Branner, *Journ. Geol.* vi. (1898), p. 368. See the papers of Professor Renard above cited; also F. Rutley, *Q. J. G. S.* l. (1894), p. 377.

[2] For a classification of tuffs and tuffaceous deposits see E. Reyer, *Jahrb. K. K. Geol. Reichsanst.* xxxi. (1881), p. 57.

that of the lava from which they have been thrown up. Usually they are porous or finely vesicular in texture.

**Volcanic Sand, Volcanic Ash**—the finer detritus erupted from volcanic orifices, consisting partly of rounded and angular fragments, up to about the size of a pea, derived from the explosion of lava within eruptive vents, partly of vast quantities of microlites and crystals of some of the minerals of the lava. The finest dust is in a state of extremely minute subdivision. When examined under the microscope, it is sometimes found to consist not only of minute crystals and microlites, but of volcanic glass, which may be observed adhering to the microlites or crystals round which it flowed when still part of the fluid lava. The presence of minutely cellular fragments is characteristic of most volcanic fragmental rocks, and this structure may commonly be observed in the microscopic fragments and filaments of glass. A characteristic feature of these minute fragments is the frequent occurrence among them of semi-circular or elliptical ("hour-glass") shapes, which evidently represent the sides of vesicles or pores that enclosed vapour or gas in the molten rock, and were disrupted and blown out during volcanic explosions.

When these various materials are allowed to accumulate, they become consolidated and receive distinctive names. In cases where they fall into the sea or into lakes, they are liable at the outer margin of their area to be mingled with, and insensibly to pass into ordinary non-volcanic sediment. Hence we may expect to find transitional varieties between rocks formed directly from the results of volcanic explosion and those which arise as ordinary sedimentary deposits.

**Volcanic Conglomerate**—a rock composed mainly or entirely of rounded or subangular fragments, chiefly or wholly of volcanic rocks, in a paste of the same materials, usually exhibiting a stratified arrangement, and often found intercalated between successive sheets of lava. Conglomerates of this kind may have been formed by the accumulation of rounded materials ejected from volcanic vents; or as the result of the aqueous erosion of previously solidified lavas, or by a combination of both these processes. Well-rounded and smoothed stones almost certainly indicate long-continued water-action, rather than trituration in a volcanic vent. In the Western Territories of the United States vast tracts of country are covered with masses of such conglomerate, sometimes 2000 feet thick. Captain Dutton has shown that similar deposits are in course of formation there now, merely by the influence of disintegration upon exposed lavas.[1]

Volcanic conglomerates receive different names according to the nature of the component fragments; thus we have *basalt-conglomerates*, where these fragments are wholly or mainly of basalt, *trachyte-conglomerates*, *andesite-conglomerates*, *phonolite-conglomerates*, &c.

**Volcanic Breccia** resembles Volcanic Conglomerate, except that the stones are angular, and the rock usually shows no trace of stratification. This angularity indicates an absence of aqueous erosion, and, under the circumstances in which it is found, usually points to immediately adjacent volcanic explosions. There is a great variety of breccias, as *basalt-breccia*, *diabase-breccia*, &c. Some of the most marvellous accumulations of this kind of materal occur in the western parts of the United States, where they have been studied both stratigraphically and petrographically by the officers of the United States Geological Survey.[2]

**Volcanic Agglomerate**—a tumultuous assemblage of blocks of all sizes up to masses

[1] 'High Plateaux of Utah,' p. 77.

[2] See Mr. Arnold Hague's excellent account of these rocks in the Absaroka Folio of the Survey, and in part i. of *Monograph* xxxii.; the petrography will be found, by Mr. Iddings and others, in part ii. of the same *Monograph*. Compare also the description by Mr. W. H. Weed of the great Cretaceous volcanic conglomerates, agglomerates, and breccias in the Livingston Formation of Montana, *Bull. U. S. G. S.* No. 105 (1893).

several yards in diameter, met with in the "necks" or pipes of old volcanic orifices. The stones and paste are commonly of one or more volcanic rocks, such as rhyolite, andesite or basalt, but they include also fragments of the surrounding rocks, whatever these may be, through which the volcanic orifice has been drilled. As a rule, agglomerate is devoid of stratification ; but sometimes it includes portions which have a more or less distinct arrangement into beds of coarser and finer detritus, often placed on end, or inclined in different directions at high angles, as described in Book IV. Part VII. Sect. i. § 4.

**Volcanic Tuff.**—This general term may be made to include all the finer kinds of volcanic detritus, ranging, on the one hand, through coarse gravelly deposits into conglomerates, and on the other, into exceedingly compact fine-grained rocks, formed of the most impalpable kind of volcanic dust. Some modern tuffs are full of microlites, derived from the lava which was blown into dust. Others are formed of small rounded or angular grains of different lavas, with fragments of various rocks through which the volcanic funnels have been drilled. The tuffs of earlier geological periods have often been so much altered, that it is difficult to state what may have been their original condition.[1] The absence of microlites and glass in them is no proof that they are not true tuffs ; for the presence of these bodies depends upon the nature of the lavas. If the latter were not vitreous and microlitic, neither would be the tuffs derived from them. In the Carboniferous volcanic area of Central Scotland, the tuffs are made up of débris and blocks of the basaltic lavas, and, like these, are not microlitic, though in some places they abound in fragments of the basic glass called palagonite. (Fig. 22, and *infra*, p. 175.)

Fig. 22.—Microscopic Structure of Carboniferous Palagonite Tuff from Burntisland, Fife.

Tuffs have consolidated sometimes under water, sometimes on dry land. As a rule, they are distinctly stratified. Near the original vents of eruption they commonly present rapid alternations of finer and coarser detritus, indicative of successive phases of volcanic activity. They necessarily shade off into the sedimentary formations with which they were contemporaneous. Thus, we have tuffs passing gradually into shale, limestone, sandstone, &c. The intermediate varieties have been called *ashy shale*, *tuffaceous shale*, or *shaley tuff*, &c. From the circumstances of their formation, tuffs frequently preserve the remains of plants and animals, both terrestrial and aquatic. Those of Monte Somma contain fragments of land-plants and shells. Some of those of Carboniferous age in Central Scotland have yielded crinoids, brachiopods, and other marine organisms. Like the other fragmentary volcanic rocks, the tuffs may be subdivided according to the nature of the lava from the disintegration of which they have been formed. Thus we have *rhyolite-tuffs*, *trachyte-tuffs*, *andesite-tuffs*, *basalt-tuffs*, &c. A few varieties with special characteristics may be mentioned here.[2]

[1] Mr. Hutchings has made some interesting observations on the structure of some of the Lower Silurian tuffs and tuffaceous slates of the north of England, *Geol. Mag.* 1892, pp. 154, 218.

[2] On the occurrence and structure of tuffs, see J. C. Ward, *Q. J. Geol. Soc.* xxxi. p. 388 ; Reyer, *Jahrb. Geol. Reichsanst.* 1881, p. 57 ; A. G., *Trans. Roy. Soc. Edin.* xxix., 'Ancient Volcanoes of Great Britain,' p. 31 ; Vogelsang, *Z. Deutsch. Geol. Ges.* xxiv. p. 543 ; Penck, *op. cit.* xxxi. p. 504 ; A. Bemrose, *Q. J. G. S.* 1894, p. 603. On the basalt-tuffs of Scania, F. Eichstadt, *Sveriges Geol. Undersökn*, ser. c. No. 58 (1883). On the volcanic

**Trass**—a pale yellow or grey rock, rough to the feel, composed of an earthy or compact pumiceous dust, in which fragments of pumice, trachyte, greywacke, basalt, carbonised wood, &c., are imbedded. It has filled up some of the valleys of the Eifel, where it is largely quarried as a hydraulic mortar.

**Peperino**—a dark-brown, earthy or granular tuff, found in considerable quantity among the Alban Hills near Rome, and containing abundant crystals of augite, mica, leucite, magnetite, and fragments of crystalline limestone, basalt, and leucite-lava. The name Peperite has been applied in Auvergne to certain volcanic breccias and tuffs of Tertiary age, some of which fill up volcanic vents, as is well seen on the south-east side of the hill of Gergovia; while others appear to be intercalated among the lacustrine Tertiary strata, and to include fresh-water shells.[1]

**Palagonite-Tuff**—a bedded aggregate of dust and fragments of basaltic lava, among which are conspicuous angular pieces and minute granules of the pale yellow, green, red, or brown altered basic glass called palagonite. This vitreous substance is intimately related to the basalts (p. 236). It appears to have gathered within volcanic vents and to have been emptied thence, not in streams, but by successive aeriform explosions, and to have been subsequently more or less altered. The percentage composition of a specimen from the typical locality, Palagonia, in the Val di Noto, Sicily, was estimated by Sartorius von Waltershausen to be: silica, 41·26; alumina, 8·60; ferric oxide, 25·32; lime, 5·59; magnesia, 4·84; potash, 0·54; soda, 1·06; water, 12·79. This rock is largely developed among the products of the Icelandic and Sicilian volcanoes;[2] it occurs also in the Eifel, Nassau, Auvergne, Scania, Faroe Isles, Canary Islands, New Zealand, and other places. It has been found to be one of the characteristic features of tuffs of Carboniferous age in Central Scotland[3] (Fig. 22).

**Schalstein.**—Under this name, German petrographers have placed a variety of green, grey, red, or mottled fissile rocks, impregnated with carbonate of lime. They are interstratified with the Devonian formations of Nassau, the Harz and Devonshire, and with the Silurian rocks of Bohemia. They sometimes contain fragments of clay-slate, and are occasionally fossiliferous. They present amygdaloidal and porphyritic, as well as perfectly laminated structures. Probably they are in most cases true diabase-tuffs, but sometimes they may be forms of diabase-lavas, which, like the stratified formations in which they lie, have undergone alteration, and in particular have acquired a more or less distinctly fissile structure, as the result of lateral pressure and internal crushing.[4]

### 4. Rocks of Organic Origin.

This series includes deposits formed either by the growth and decay of organisms *in situ*, or by the transport and subsequent accumulation of their remains. These may

tuffs used for building purposes in the Roman Campagna, A. Verri, *B. S. G. Ital.* xi. (1892), pp. 63-75. On the metamorphism of tuffs into lava-like rocks, see Dutton's "High Plateaux of Utah" (*U. S. Geograph. and Geol. Survey of Rocky Mounts.*), 1880, p. 79.

[1] According to M. Michel-Lévy and some other French geologists, however, these rocks are to be regarded as intrusive masses. The evidence for this view is fully set forth in No. 87 of the *Bull. Cart. Géol. France* (1902), by M. J. Giraud. The view stated in the text was formed by me on the ground in Auvergne, and is based not only on observations there, but on a wide experience of the similar but much more clearly presented evidence of the younger volcanic rocks in Central Scotland.

[2] S. von Waltershausen, 'Ueber die Vulkanischen Gesteine in Sicilien und Island,' 1853, pp. 179, 424. H. Pjeturson, *Scot. Geograph. Mag.* xvi. (1900).

[3] 'Ancient Volcanoes of Great Britain,' vol. i. pp. 33, 61, 422; ii. pp. 44, 57, 223.

[4] Oppermann, 'Dissertation über Schalstein und Kalktrapp,' Frankfort, 1836. C. Koch, *Jahrb. Ver. Nat. Nassau*, xiii. (1858), pp. 216, 238. J. A. Phillips, *Q. J. G. S.* xxxii. p. 155; xxxiv. p. 471. Hutchings, *Geol. Mag.* 1892, pp. 154, 218.

be conveniently grouped, according to their predominant chemical ingredient, into Calcareous, Siliceous, Phosphatic, Glauconitic, Carbonaceous, and Ferruginous.

1. CALCAREOUS.—Besides the calcareous formations which occur among the stratified crystalline rocks as results of the deposition of chemical precipitates (p. 190), a more important series is derived from the remains of living organisms, either by growth on the spot or by transport and accumulation as mechanical sediment. To by far the larger part of the limestones intercalated in the rocky framework of our continents, an organic origin may with probability be assigned. It is true, as has been above mentioned (p. 156), that limestone, formed of the remains of animals or plants, is liable to an internal crystalline rearrangement, the effect of which is to obscure or obliterate the organic structure. Hence, in many of the older limestones, no trace of any fossils can be detected, and yet these rocks were almost certainly formed of organic remains. An attentive microscopic study of organic calcareous structures, and of the mode of their replacement by crystalline calcite, sometimes detects indications of former organisms, even in the midst of thoroughly crystalline materials.[1]

**Limestone** (Calcaire, Kalkstein)—essentially a mass of calcium-carbonate, sometimes nearly pure, and entirely or almost entirely soluble in hydrochloric acid, sometimes loaded with sand, clay or other intermixture. Few rocks vary more in texture and composition. It may be a hard, close-grained mass, breaking with a splintery or conchoidal fracture; or a crystalline rock built up of fine crystalline grains of calcite, and resembling loaf-sugar in colour and texture; or a dull, earthy, friable, chalk-like deposit; or a compact, massive, finely granular rock resembling a close-grained sandstone or freestone. As its normal hardness is about 3, it can easily be scratched with a knife, and the white powder gives a copious effervescence with acid. The specific gravity naturally varies according to the impurity of the rock, ranging from 2·5 to 2·8. The colours, too, vary extensively, the most common being shades of blue-grey and cream-colour passing into white. Some limestones are highly siliceous, the calcareous matter having been accompanied with silica in the act of deposition; others are argillaceous, sandy, ferruginous, dolomitic, or bituminous. Carbonate of magnesia in minute proportion is present in most calcareous organisms, and, being less soluble than carbonate of lime, its amount in calcareous deposits may in consequence be increased.[2] Although by far the larger number of limestones are of organic origin, their original clastic character, owing to internal rearrangement, has frequently been changed into a crystalline one. Those which have been deposited as chemical precipitates without the co-operation of the agency of plants or animals are described at p. 190. But it is often quite impossible to speak with confidence as to the derivation of a limestone, for by infiltrating water carrying calcium-carbonate in solution, the original texture of the rock may be entirely obscured or obliterated. We are here concerned with those varieties which have resulted from organic secretions.

Limestone composed of the remains of calcareous organisms is found in layers which range from mere thin laminæ up to massive beds, several feet or even yards in thickness. In some instances, such as that of the Carboniferous or Mountain limestone of Britain and Belgium, and that of the Coal-measures in Wyoming and Utah, it occurs in continuous superposed beds to a united thickness of several thousand feet, and extends for hundreds of square miles, forming a rock out of which picturesque gorges, hills, and table-lands have been excavated.

Limestones of organic origin, as above remarked, vary in texture and structure, from mere soft calcareous mud or earth, evidently composed of entire or crumbled organisms, up to solid compact crystalline rock, in which indications of an organic source may

[1] Sorby, Address to Geol. Society, February 1879; and the paper of Messrs. Cornish and Kendall, cited *ante*, p. 156. Gümbel has suggested that the different durability of the calcite and aragonite organic forms may be due rather to structure than mineral composition.

[2] On these carbonates see Hardman, *Proc. Roy. Irish Acad.* ii. (1877), p. 705.

not be perceptible. Mr. Sorby, in the Address already cited, called renewed attention to the importance of the form in which carbonate of lime is built up into animal structures. Quoting the opinion of Rose expressed in 1858, that the diversity in the state of preservation of different shells might be due to the fact that some of them had their lime as calcite, others as aragonite, he showed that this opinion is amply supported by microscopic examination. Even in the shells of a recent raised beach, he observed that the inner aragonite layer of the common mussel had been completely removed, though the outer layer of calcite was well preserved. In some shelly limestones containing casts, the aragonite shells have alone disappeared, and where these still remain represented by a calcareous layer, this has no longer the original structure, but is more or less coarsely crystalline, being in fact a pseudomorph of calcite after aragonite, and quite unlike contiguous calcite shells, which retain their original microscopical and optical characters.[1]

Not only is limestone subject to the conversion of original aragonite into calcite, but further (metasomatic) changes frequently alter its chemical composition. By a replacement of half its substance by carbonate of magnesia, it is converted into dolomite (Dolomitisation). In other cases the carbonate of lime has been replaced by carbonate of iron which, on oxidation, becomes magnetite, hæmatite, or limonite. This change appears to be specially apt to occur in oolitic bands, hence probably many or most of the oolitic forms of ironstone. In some cases the oolite grains of calcite have been replaced by silica, and examples may be observed in formations of all ages where calcareous organisms have had the place of their carbonate of lime taken by flint or chert (Silicification). A further chemical alteration of organic limestone is seen where the calcite is replaced, in large part or wholly, by phosphate of lime (Phosphatisation). To a considerable extent the calcite or aragonite of the organisms in some calcareous deposits has been replaced by glauconite (Glauconitisation). For an account of these various processes, see Book III. Part II. Sect. iii. § 3.

The following list comprises some of the more distinctive and important forms of organically-derived limestones.

Lake-Marl (Shell-Marl)—a soft, white, earthy, or crumbling deposit, formed in lakes and ponds by the accumulation of the remains of fresh-water algæ, shells and *Entomostraca* on the bottom. When such calcareous deposits become solid compact stone, they are known as *fresh-water* (*lacustrine*) *limestones*, which are generally of a smooth texture, and either dull white, pale grey, or cream-coloured, their fracture slightly conchoidal, rarely splintery.[2]

Lumachelle—a compact, dark grey or brown limestone, charged with ammonites or other fossil shells, which are sometimes iridescent, giving bright green, blue, orange, and dark red tints (fire-marble).

Calcareous (Foraminiferal) Ooze—a white or grey calcareous mud, of organic origin, found covering vast areas of the floor of the Atlantic and other oceans, and formed mostly of the remains of *Foraminifera*, particularly of forms of the genus

[1] The student will find the Address from which these citations are made full of suggestive matter in regard to the origin and subsequent history of limestones. See also Cornish and Kendall, "On the Mineralogical Constitution of Calcareous Organisms," already cited, *Geol. Mag.* 1888, p. 66; Kendall, *Brit. Assoc.* 1896, p. 789. Mr. Wethered has described the minute structure of a number of limestones; see, for example, his paper on the Wenlock Limestones, *Q. J. G. S.* xlix. (1893), p. 286. The Hirnant Limestone has been described by Mr. Fulcher, *Geol. Mag.* 1892, p. 114. An exhaustive account of limestones, chiefly from the point of view of their use in architecture and the arts, will be found in Mr. S. M. Burnham's 'History and Uses of Limestones and Marbles,' pp. xv., 392, with 48 coloured reproductions of well-known ornamental stones.

[2] See a "Contribution to the Natural History of Marl," by C. A. Davis, *Journ. Geol.* viii. (1900), pp. 485-497.

*Globigerina* (Fig. 23). Further account of this and other organic deep-sea deposits is given in Book III. Part II. Sect. iii. When this material has been solidified into stone it forms Foraminiferal Limestone.[1]

Shell-Sand (Foraminiferal-sand, Nullipore-sand)—a deposit composed in great measure or wholly of comminuted calcareous organisms, found commonly on a low shelving coast exposed to prevalent on-shore winds. The organisms are sometimes the detritus of calcareous sea-weeds (nullipores) or foraminifera, broken-up shells, &c. When thrown above the reach of the waves and often wetted with rain, or by trickling runnels of water, this deposit is apt to become consolidated into a more or less firm limestone, owing to the solution and redeposit of lime round the grains of shell (p. 156).[2]

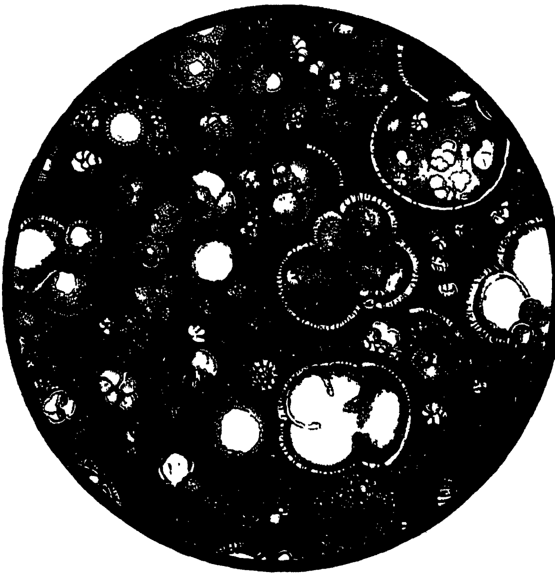

Fig. 23.—Foraminiferal (Globigerina) Ooze, dredged by the *Challenger* Expedition in Lat. 50° 1′ S., Long. 123° 4′ E., from a depth of 1800 fathoms (magnified 50 Diameters).

Coral-rock—a limestone formed by the continuous growth of coral-building polyps. This substance affords an excellent illustration of the way in which organic structure may be effaced from a limestone entirely formed of the remains of once living animals. Though the skeletons of the reef-building corals remain distinct on the upper surface, those of their predecessors beneath them are gradually obliterated by the passage through them of percolating water, dissolving and redepositing calcium carbonate. We can thus understand how a mass of crystalline limestone may have been produced from one formed out of organic remains, without the action of any subterranean heat, but merely by the permeation of water from the surface.[3]

[1] On foraminiferal limestone, see F. Chapman, *Geol. Mag.* 1900, pp. 316, 367. A detailed comparison of globigerina ooze with chalk will be found in chap. xiii. of Cayeux, 'Étude Microgr. Terr. Sedim.'

[2] On Æolian limestones see an interesting paper by Dr. J. W. Evans on "Mechanically-formed Limestones from Junagurh and other Localities," *Q. J. G. S.* lvi. (1900), p. 559.

[3] See the section Coral-reefs in Book III. Part II. Sect. iii. § 3; also Dana's 'Coral and Coral Islands,' p. 354; and the account of the Devonian and Carboniferous limestones

Chalk—a white soft rock, meagre to the touch, soiling the fingers, formed of a fine calcareous flour derived from the remains of *Foraminifera*, echinoderms, mollusks, and other marine organisms. By making thin slices of the rock and examining them under the microscope, Sorby found that Foraminifera, particularly *Globigerina*, and single detached cells of comparatively shallow-water forms, probably constitute less than half of the rock by bulk (Fig. 21), the remainder consisting of detached prisms of the outer calcareous layer of *Inoceramus*, fragments of *Ostrea, Pecten*, echinoderms, spicules of sponges, &c. A microscopic investigation of chalk from the neighbourhood of Lille showed that, besides the usual organic constituents, the rock contains minute grains and crystals of quartz, tourmaline, zircon, rutile, garnet and felspars,[1] these minerals being among the most widely diffused and persistent ingredients in the finer sediments that are derived from the denudation of crystalline rocks (see p. 163).

Crinoidal (Encrinite) Limestone—a rock composed in great part of crystalline joints of encrinites, with *Foraminifera*, corals and mollusks. It varies in colour from white or pale grey, through shades of bluish-grey (sometimes yellow or brown, less commonly red) to a dark grey or even black colour. It is abundant among Palæozoic formations, being in Western Europe especially characteristic of the lower part of the Carboniferous system.

2. SILICEOUS.—Silica is directly eliminated from both fresh and salt water by the vital growth of plants and animals. (Book III. Part II. Sect. iii.)

**Diatom-earth, Tripolite** (Infusorial earth, Kieselguhr)—a siliceous deposit formed chiefly of the frustules of diatoms, laid down both in salt and in fresh water. Wide areas of it are now being deposited on the bed of the South Pacific (*Diatom-ooze*, Fig. 185). In Virginia, United States, an extensive tract occurs covered with diatom-earth to a depth of 40 feet. The same substance likewise underlies peat-mosses, probably as an original lake-deposit. It is used as *Tripoli powder* for polishing purposes, and in the manufacture of high explosives (p. 609).

**Radiolarian ooze**—a pale chalk-like abysmal marine deposit consisting mainly of the remains of siliceous radiolarians and diatoms. It is further referred to at p. 624.

**Flint** (Silex, Feuerstein)—a grey or black, excessively compact rock, with the hardness of quartz and a perfect conchoidal fracture, its splinters being translucent on the edges. It consists of an intimate mixture of crystalline insoluble silica and of amorphous silica soluble in caustic potass. Its dark colour, which can be destroyed by heat, arises chiefly from the presence of carbonaceous matter. Flint occurs abundantly as nodules, dispersed in layers through the Upper Chalk of England and the north-west of Europe, likewise in Jurassic limestones in the south of England. It frequently encloses organisms such as sponges, echini and brachiopods. It has been deposited from either salt or fresh water, at first through organic agency, and subsequently by chemical precipitation round the already deposited silica. (Book III. Part II. Sect. iii.) Thus, in some cases, as in the spicules of sponges, the silica has had a directly organic origin, having been secreted from sea-water by the living organisms. In other cases, where, for example, we find a calcareous shell, or echinus, or coral converted into silica, it would seem that the substitution of silica for calcium-carbonate has been effected by a process of chemical pseudomorphism, either after or during the formation of the limestone.

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in the present volume. Dupont has shown that many of the massive limestones of Belgium have been formed by reef-like masses of *Stromatopora* or allied organisms.

[1] L. Cayeux, *Ann. Soc. Géol. Nord.* xvii. (1890), p. 283. This geologist has since published a detailed account of the minute structure and composition of the Chalk and other Cretaceous deposits of France in his large 4to volume, cited on p. 106. To the minerals above mentioned as having been detected in the Chalk there have since been added magnetite, muscovite, both orthoclase and plagioclase, anatase, brookite, chlorite, staurotide, garnet, apatite, corundum, and ilmenite (*op. cit.* p. 257). See also Messrs. Jukes Browne and Hill on Chalk, *Q. J. G. S.* xlii. p. 216; xliii. p. 544; xlv. p. 403.

The vertical ramifying masses of flint in Chalk show that the calcareous ooze had to some extent accumulated before the segregation of these masses.[1] Chert (phthanite) is a name applied to impure calcareous varieties of flint, in layers and nodules which are found among the Palæozoic and later formations, especially but not exclusively in limestones.[2]

3. PHOSPHATIC.—Phosphate of lime, widely distributed in nature in minute quantities, is in various places aggregated into masses of considerable dimensions. It occurs as the mineral apatite, which is occasionally abundant in crystalline limestones, gneisses, and various igneous rocks. But we have here to deal with those deposits of phosphate of lime which are found made up of detrital organic material and intercalated among sedimentary strata. A few invertebrata contain phosphate of lime. Among these may be mentioned the brachiopods *Lingula* and *Orbicula*,[3] also *Conularia*, *Serpulites*, and some recent and fossil crustacea. The shell of the recent *Lingula ovalis* was found by Hunt to contain, after calcination, 61 per cent of fixed residue, which consisted of 85·70 per cent of phosphate of lime, 11·75 carbonate of lime, and 2·80 magnesia. The bones of vertebrate animals likewise contain about 60 per cent of phosphate of lime, while their excrement sometimes abounds in the same substance. Hence deposits rich in phosphate of lime have resulted from the accumulation of animal remains from at least Cambrian times up to the present days. In the Lower Cambrian strata of New Brunswick phosphatic nodules are aggregated into a layer two inches thick and are also scattered through the adjoining sandstones. They are crowded with tests of protozoa (foraminifera, sponges), and contain about 15 per cent of phosphoric acid. Other nodules in the same formation are made up of comminuted *Lingulae*.[4] Associated with the Bala limestone, in the Lower Silurian series of North Wales, is a band composed of concretions cemented in a black, graphitic, slightly phosphatic matrix, and containing usually 64 per cent of phosphate of lime (phosphorite).[5] The tests of the trilobites and other organisms among the Cambrian rocks of Wales also contain phosphate of lime, sometimes to the extent of 20 per cent.[6] A chemical transformation takes place by which the calcareous matter of organisms, shells, sponges, &c. is replaced by calcium-phosphate. This process (phosphatisation) will be more fully noticed in Book III. Part II. Sect. iii. § 3. Phosphatic, though certainly far inferior in extent and importance to calcareous, and even to siliceous, formations, are often of singular geological interest, as well as of considerable economic importance. The following examples may serve as illustrations. (Book III. Part II. Sect. iii. § 3.)

[1] On formation of chalk-flints, see Book III. Part II. Sect. iii. § 3.

[2] Consult Hull and Hardman, *Trans. Roy. Dublin Soc.* i. (1878), p. 71. Renard, *Bull. Acad. Roy. Belgique*, 2nd ser. vol. xlvi. p. 471. Sollas, *Ann. Mag. Nat. Hist.* vii. (1881), p. 141. *Scientific Proc. Roy. Dublin Soc.* vi. (1887), Part i. G. J. Hinde, *Geol. Mag.* 1887, p. 435 ; 1888, p. 241 (Permo-Carboniferous cherts of Spitzbergen). E. O. Tovey on Cambrian and Carboniferous cherts in Missouri, *Amer. Journ. Sci.* xlviii. (1894), p. 401. Bands of radiolarian chert occupy persistent horizons among the Lower Silurian rocks of Southern Scotland, and have been met with in other parts of Britain in the same stratigraphical series.

[3] Sterry Hunt, *Amer. Journ. Soc.* xvii. (1854), p. 236. Logan's 'Geology of Canada,' 1863, p. 461.

[4] W. D. Matthew, *Trans. New York Acad. Sci.* xii. (1893), p. 108.

[5] D. C. Davies, *Q. J. G. S.* xxxi. (1875), p. 357. See also *Geol. Mag.* 1875, pp. 188, 238 ; 1877, p. 257. A good account of the phosphatic deposits of North America and Europe, by R. A. F. Penrose, junr., will be found in *Bull. No.* 46 *U. S. G. S.* (1888), with a bibliography of the subject. C. W. Hayes, 17*th Ann. Rep. U. S. G. S.* Part ii. ; *21st Ann. Rep. U. S. G. S.* Part iii. (1901). G. H. Eldridge, "On Phosphates of Florida," *Amer. Inst. Min. Engin.* 1892.

[6] Hicks, *Q. J. G. S.* xxxi. p. 368.

**Guano**—a deposit consisting mainly of the droppings of sea-fowl, formed on islands in rainless tracts off the western coasts of South America and of Africa. It is a brown, light, powdery substance with a peculiar ammoniacal odour, and occurs in deposits sometimes more than 100 feet thick. By long exposure to rain or sea-water the soluble constituents are removed, and a mass of material, insoluble or almost insoluble in water, is left behind, varying from the consistency of loose powder to that of a hard compact stone. Hence the substance has been divided for commercial purposes into *soluble guano* and *leached guano*. Analyses of American guano give—combustible organic matter and acids, 11·3; ammonia (carbonate, urate, &c.), 31·7; fixed alkaline salts, sulphates, phosphates, chlorides, &c., 8·1; phosphates of lime and magnesia, 22·5; oxalate of lime, 2·6; sand and earthy matter, 1·6; water, 22·2. This remarkable substance is highly valuable as a source of artifical manures. (Book III. Part II. Sect. iii. § 3.)

**Bone-Breccia**—a deposit consisting largely of fragmentary bones of living or extinct species of vertebrates, especially mammalia, found sometimes under stalagmite on the floors of limestone caverns, more or less mixed with earth, sand or lime. In some older geological formations, bone-beds occur, formed largely of the remains of reptiles or fishes, as the "Lias bone-bed" and the "Ludlow bone-bed."

**Coprolitic nodules** and **beds** [1]—are formed of the accumulated excrement (coprolites) of vertebrated animals. Among the Carboniferous shales of the basin of the Firth of Forth, coprolitic nodules are abundant, together with the bones and scales of the larger ganoid fishes which voided them: abundance of broken scales and bones of the smaller ganoids can usually be observed in the coprolites. Among the Lower Silurian rocks of Canada, numerous phosphatic nodules, supposed to be of coprolitic origin, occur.[2] The phosphatic beds of the Cambridgeshire Cretaceous rocks have been largely worked as a source of artificial manure. In popular and especially commercial usage, the word "coprolitic" is applied to nodular deposits which can be worked for phosphate of lime, though they may contain few or no true coprolites.

**Phosphatic Chalk.**—In the Chalk of France and Belgium, more sparingly in that of England, certain layers occur where the original calcareous matter has been replaced to a considerable extent by phosphate of lime. Such bands have frequently a brownish tint, which on examination is found to result from the abundance of minute brown grains composed mainly of phosphates. By the process of phosphatisation above referred to, the foraminifera and other minuter or fragmentary fossils have been changed into this brown substance. The proportion of phosphate of lime ranges up to 45 per cent or more.[3]

4. Glauconitic.—Many sandstones and other sedimentary deposits have a greenish colour from the presence of abundant glauconite, which coats their grains and is dispersed in irregular nodules, veins and partings (glauconitisation). As already remarked, this substance is found filling the chambers of recent polythalamia off the coasts of Florida, and abundantly diffused over certain parts of the sea-floor, especially in the green muds. In the stratified formations of the earth's crust many examples of similar deposition have been observed. In the Cambrian system of New Brunswick abundant grains of glauconite occur associated with foraminifera and with some phosphate of lime.[4] The Secondary and Tertiary formations likewise include excellent illustrations of glauconitic deposits. The Cretaceous members known as the Lower and Upper Greensand of England owe their colour to the presence of the same green mineral. (Book III. Part II. Sect. iii. § 3.)

5. Carbonaceous.—The formations here included have almost always resulted from the decay and entombment of vegetation on the spot where it grew, sometimes by the

[1] On the origin of phosphatic nodules and beds, see Gruner, *B. S. G. F.* xxviii. (2nd ser.), p. 62. Martin, *op. cit.* iii. (3rd ser.), p. 273. [2] Logan's 'Geology of Canada,' p. 461.

[3] See A. Renard and J. Cornet, *Bull. Acad. Roy. Belgique*, xxi. (1891), p. 126. A. Strahan, *Q. J. G. S.* xlvii. (1891), and the papers cited in Book III. Part II. Sect. iii. § 3.

[4] W. D. Matthew, *Trans. New York Acad. Sci.* xii. (1893), p. 111.

drifting of the plants to a distance and their consolidation there. (See Book III. Part II. Sect. iii. § 3.) In the latter case, they may be mingled with inorganic sediment so as to pass into carbonaceous shale. Occasionally the carbonaceous material has been mainly supplied by animal remains.

**Peat** (Tourbe, Torf)—vegetable matter, more or less decomposed and chemically altered, found throughout temperate climates in boggy places where marshy plants grow and decay. It varies from a pale yellow or brown fibrous substance, like turf or compressed hay, in which the plant-remains are abundant and conspicuous, through various stages of increasing solidity (and sometimes with a laminated structure) to a compact dark brown or black material, resembling black clay when wet, and some varieties of lignite when dried. The nature and proportions of the constituent elements of peat, after being dried at 100° C., are illustrated by the analysis of an Irish example which gave—carbon, 60·48 ; hydrogen, 6·10 ; oxygen, 32·55 ; nitrogen, 0·88 ; while the ash was 3·30.[1] There is always a large proportion of water which cannot be driven off even by drying the peat. In the manufacture of compressed peat for fuel this constituent, which of course lessens the value of the peat as compared with an equal weight of coal, is driven off to a great extent by chopping the peat into fine pieces, and thereby exposing a large surface to evaporation. The ash varies in amount from less than 1·00 to more than 65 per cent, and consists of sand, clay, ferric oxide, sulphuric acid, and minute proportions of lime, soda, potash and magnesia.[2] Under a pressure of 6000 atmospheres peat is converted into a hard, black, brilliant substance having the physical aspect of coal, and showing no trace of organic structure.[3]

**Lignite (Brown Coal)**—compact or earthy, compressed and chemically altered vegetable matter, often retaining a lamellar or ligneous texture, with stems showing woody fibre crossing each other in all directions. It varies from pale brown or yellow to deep brown or black. Some shade of brown is the usual colour, whence the name *Brown Coal*, by which it is often known. It contains from 55 to 75 per cent of carbon, has a specific gravity of 0·5 to 1·5, burns easily to a light ash with a sooty flame and a strong burnt smell. It occurs in beds chiefly among the Tertiary strata, under conditions similar to those in which coal is found in older formations. It may be regarded as a stage in the alteration and mineralisation of vegetable matter, intermediate between peat and true coal. Different varieties of lignite have received special names to denote their peculiarities, such as Pitch-coal, fibrous or woody Brown coal, Paper-coal. The Surturbrand of Iceland and the Faroe Islands is a variety of brown coal which occurs in seams intercalated among the Tertiary basalts and palagonite tuffs. Similar layers, including some black glossy coal, are found here and there in the corresponding volcanic series in the west of Scotland and north of Ireland.

**Coal**—a compact, usually brittle, velvet-black to pitch-black, iron-black, or dull, sometimes brownish rock, with a greyish-black or brown streak, and in some varieties a distinctly cubical cleavage, in others a conchoidal fracture. It contains from 75 to 90 per cent of carbon, 3 to 20 of oxygen, ½ to 5½ of hydrogen, 0 to 2½ of nitrogen, and from 1 to 30 of ash, with frequently a small percentage of sulphur, generally in the form of iron-disulphide. It has a specific gravity of 1·2 to 1·5, and burns with comparative readiness, giving a clear flame, a strong aromatic or bituminous smell, some varieties fusing and caking into cinder, others burning away to a mere white or red ash. Though it consists of compressed vegetation, no trace of organic structure is usually apparent.[4]

[1] For analyses of various peats from Baden, see Nessler, *Neues Jahrb.* 1861, p. 62. ; J. Websky, *Journ. Prakt. Chem.* xcii. (1864), p. 92.

[2] See Senft's 'Humus-, Marsch-, Torf- und Limonit-bildungen,' Leipzig, 1862. J. J. Früh, 'Ueber Torf und Dopplerit,' Zürich, 1883, and the various memoirs quoted *postea*, p. 606.

[3] Spring, *Bull. Acad. Roy. Bruxelles*, xlix. (1880), p. 367.

[4] On the influence of pressure on the formation of coal, see Frémy, *Compt. rend.* 20th May 1879. Spring, *ut supra cit.*

An attentive examination, however, will often disclose portions of stems, leaves, &c., or at least of carbonised woody fibre. Some kinds are almost wholly made up of the spore-cases of lycopodiaceous plants (Fig. 24). There is reason to believe that different varieties of coal may have arisen from original diversities in the nature of the vegetation out of which they were formed. Various types are recognised as caking coal, non-

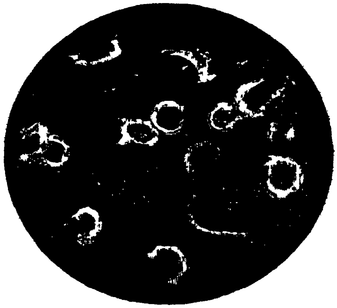

Fig. 24.—Microscopic Structure of Dalkeith Coal, showing Lycopodiaceous Sporangia (magnified 200 Diameters).

caking coal, cannel (or parrot) coal, jet. The accompanying table shows the chemical gradation between unaltered vegetation and the more highly mineralised forms of coal.

TABLE SHOWING THE GRADUAL CHANGE IN COMPOSITION FROM WOOD TO CHARCOAL.[1]

| Substance. | Carbon. | Hydrogen. | Oxygen. | Disposable Hydrogen, *i.e.*, over and above what is required to form water. |
|---|---|---|---|---|
| 1. Wood (mean of several analyses) . | 100 | 12·18 | 83·07 | 1·80 |
| 2. Peat ( ,, ,, ,, ) . | 100 | 9·85 | 55·67 | 2·89 |
| 3. Lignite (mean of 15 varieties) . | 100 | 8·37 | 42·42 | 3·07 |
| 4. Ten-yard coal of S. Staffordshire basin . . . . . | 100 | 6·12 | 21·23 | 3·47 |
| 5. Steam coal from the Tyne . . | 100 | 5·91 | 18·32 | 3·62 |
| 6. Pentrefelin coal of S. Wales . . | 100 | 4·75 | 5·28 | 4·09 |
| 7. Anthracite from Pennsylvania, U.S. | 100 | 2·84 | 1·74 | 2·63 |

Coal occurs in seams or beds intercalated between strata of sandstone, shale, fireclay, &c., in geological formations of Palæozoic, Secondary, and Tertiary age. It should be remembered that the word coal is rather a popular than a scientific term, being indiscriminately applied to any dense, black mineral substance capable of being used as fuel. Strictly employed, it ought only to be used with reference to beds of fossilised vegetation, the result either of the growth of plants on the spot or of the drifting of them thither.

The following analyses show the chemical composition of peat, lignite, and some of the principal varieties of coal[2]:—

[1] Percy's 'Metallurgy,' i. p. 268.

[2] From Percy's 'Metallurgy,' vol. i. A Committee was appointed by the British Association some years ago to ascertain the proximate chemical constituents of coal, and has briefly reported in the *Rep. B. A.* for 1894, p. 246, and for 1896, p. 340. On the process of the conversion of vegetable remains into lignite and coal, see Book III. Part II. Sect. iii. § 3.

| | Peat. | Lignite. | Coking Coal. | Non-Caking Coal. | Cannel Coal. | Anthracite. |
|---|---|---|---|---|---|---|
| | Devonshire. | Bovey Tracey, Devon. | Northumberland. | S. Staffordshire. | Wigan. | S. Wales. |
| Carbon | 54·02 | 66·31 | 78·69 | 78·57 | 80·07 | 90·39 |
| Hydrogen | 5·21 | 5·63 | 6·00 | 5·29 | 5·53 | 3·28 |
| Oxygen | 28·18 | 22·86 | 10·07 | 12·88 | 8·08 | 2·98 |
| Nitrogen | 2·30 | 0·57 | 2·37 | 1·84 | 2·12 | 0·83 |
| Sulphur | 0·56 | 2·36 | 1·51 | 0·39 | 1·50 | 0·91 |
| Ash | 9·73 | 2·27 | 1·36 | 1·03 | 2·70 | 1·61 |
| Specific gravity | 0·850 | 1·129 | 1·259 | 1·278 | 1·276 | 1·392 |

These analyses are exclusive of water, which in the peat amounted to 25·56, and in the lignite to 34·66 per cent.

**Anthracite**—the most highly mineralised form of vegetation—is an iron-black to velvet-black substance, with a strong metalloidal to vitreous lustre, hard and brittle, containing over 90 per cent of carbon, with a specific gravity of 1·35–1·7. It kindles with difficulty, and in a strong draught burns without fusing, smoking, or smelling, but giving out a great heat. It is a coal from which the bituminous parts have been eliminated. It occurs in beds like ordinary coal, but in positions where probably it has been subjected to some change whereby its volatile constituents have been expelled. It is found largely in South Wales, and sparingly in the Scottish coal-fields, where the ordinary coal-seams have been approached by intrusive masses of igneous rock. It is largely developed in the great coal-field of Pennsylvania.[1] Some Lower Silurian shales are black from diffused anthracite, and have in consequence led to fruitless searches for coal.

**Oil-shale** (*Brandschiefer*)—shale containing such a proportion of hydrocarbons as to be capable of yielding mineral oil on slow distillation. This substance occurs as ordinary shales do, in layers or beds, interstratified with other aqueous deposits, as in the Scottish coal-fields. It is there in a geological sense true shale, and owes its peculiarity to the quantity of vegetable (or animal) matter which has been preserved among its inorganic constituents. It consists of fissile argillaceous layers, highly impregnated with bituminous matter, passing on one side into common shale, on the other into cannel or parrot coal. The richer varieties yield from 30 to 40 gallons of crude oil to the ton of shale. They may be distinguished from non-bituminous or feebly bituminous shales (throughout the shale districts of Scotland), by the peculiarity that a thin paring curls up in front of the knife, and shows a brown lustrous streak. Some of the oil-shales in the Lothians are crowded with the valves of ostracod crustaceans, besides scales, coprolites, &c., of ganoid fishes. The bituminous matter has probably been derived from a pulpy mass of decayed vegetation, consisting probably in large part of algæ and other simple forms, though the animal remains are sometimes so abundant as to suggest that they may have to some considerable extent contributed to the carbonaceous constituents of the original mud. One of the most famous of the oil-producing seams in the Scottish coal-field was the now exhausted seam of Boghead, which has been claimed by some geologists as a variety of cannel coal, by others as a bituminous shale or mud-stone.[2] It has given its name to a type of oil-bearing

[1] On the classification and composition of the Pennsylvania Anthracites, see C. A. Ashburner, *Science*, 14th March 1884. *Amer. Inst. Min. Engin.*, February 1886. On their origin, J. J. Stevenson, *Journ. Geol.* i. (1893), p. 677.

[2] C. E. Bertrand and B. Renault, *Ann. Soc. Géol. Nord.* xx. (1892), pp. 213-259; *Compt. rend.* cxvii. (1893), p. 593; C. E. Bertrand, *Bull. Soc. Hist. Nat. Autun*, ix. (1896); *Compt. rend. Congrès. Geol.*, Paris (1900), p. 458. See also the late Professor J. S. Newberry

minerals which are known as "Bogheads," and appear to have been formed mainly of algæ. Among these is Torbanite, which really is the original Boghead seam mined at Torbanehill, Bathgate, Linlithgowshire; and kerosene shale, a variety from New South Wales, which has been found by M. C. E. Bertrand to consist of a fundamental clear brown flocculent jelly-like base, crowded with minute rounded bodies, together with spores, grains of pollen, algæ, and débris of other vegetation. "Boghead" is worked in the Autun coal-field of France. Some of the flagstones of the Old Red Sandstone of the north of Scotland are highly bituminous, likewise the Kimmeridge clay in the Jurassic series of the south of England. Under the name "pyroschists" Sterry Hunt classed the clays or shales (of all geological ages) which are hydrocarbonaceous, and yield by distillation volatile hydrocarbons, inflammable gas, &c.

**Petroleum**, a general term, under which is included a series of natural mineral oils.[1] These are fluid hydrocarbon compounds, varying from a thin, colourless, watery liquidity to a black, opaque, tar-like viscidity, and in specific gravity from 0·8 to 1·1. The paler, more limpid varieties are generally called naphtha, the darker, more viscid kinds mineral tar, while the name petroleum, or rock-oil, has been more generally applied to the intermediate kinds. Petroleum occurs sparingly in Europe. A few localities for it are known in Britain. It is found abundantly along the country stretching from the Carpathians, through Gallicia and Moldavia; at Baku on the Caspian,[2] and in the so-called oil-regions of North America, particularly in Western Canada and Northern Pennsylvania, where vast quantities of it have been obtained. In Pennsylvania it is found especially in certain porous beds of sandstone or "sand-rocks," which occur as low down as the Old Red Sandstone, or even as the top of the Silurian system. In Canada it is largely present in still lower strata. Its origin in these ancient formations, where it cannot be satisfactorily connected with any destructive distillation of coal, is further referred to at pp. 86, 318, 357.

Reference may here be made to the abundant discharge of gaseous hydrocarbons at the places where petroleum is abundant. From a remote period the natural gas has been made use of by fire-worshippers, as at the still-preserved temple with its tower and escaping gas near Baku. So copious is the supply of gas in Pennsylvania that it is employed to light towns, and for various industrial purposes. The natural hydrocarbons have been divided into—1st, Bituminous, with marsh-gas and natural gas at the one end and intermediate kinds, fluid (naphtha, petroleum), viscous (mineral tar), and elastic (elaterite) to solid substances at the other, with anthracite to finish the list; 2nd, Resinous (amber, &c.); 3rd, Cerous (ozocerite, hatchettite); and 4th, Crystalline (fichtelite, hartite, &c.).[3]

**Amber**—a fossil resin, found in pieces of irregular shape in various Tertiary and post-Tertiary deposits. Large quantities of it are washed ashore from submarine formations under the Baltic, and also on the east coast of England. Insects have often been perfectly preserved in this substance.

on the origin of the carbonaceous matter in bituminous shales, *Ann. New York Acad. Sci.* ii. No. 12 (1883).

[1] The most comprehensive English work on this substance is 'Petroleum,' by Mr. B. Redwood, in two vols. of 900 pages, London, Griffith and Co., 1896. There are likewise a small work by R. N. Boyd, 'Petroleum, its Development and Uses,' pp. 85, London, 1896; 'Le Pétrole, l'Asphalte et le Bitume au point de vue géologique,' A. Jaccard, pp. 292, Paris, 1896. See also E. Orton, "Geological Probabilities as to Petroleum," *B. Amer. Geol. Soc.* ix. (1897), p. 85. C. Ochsenius, "Erdölbildung," *Z. D. G. G.* xlviii. (1896), pp. 239, 685.

[2] Abich, *Jahrb. Geol. Reichsanst.* xxix. (1879), p. 165. Trautschold, *Z. D. G. G.* xxvi. (1874), p. 257. See *postea*, Book III. Part I. Sect i. § 2, p. 317, where other authorities are cited.

[3] *Trans. Amer. Inst. Min. Engin.* xviii. p. 582. G. H. Eldridge, *17th Ann. Rep. U. S. Geol. Surv.* (1896), p. 916.

**Asphalt**—a smooth, brittle, pitch-like, black or brownish-black mineral, having a resinous lustre and conchoidal fracture, streak paler than surface of fracture, and specific gravity of 1·0 to 1·68. It melts at about the temperature of boiling water, and can be easily kindled, burning with a bituminous odour and a bright but smoky flame. It is composed chiefly of hydrocarbons, with a variable admixture of oxygen and nitrogen. It occurs sometimes in association with petroleum, of which it may be considered a hardened oxidized form, sometimes as an impregnation filling the pores or chinks of rocks, sometimes in independent beds. In Britain it appears as a product of the destructive distillation of coals and carbonaceous shales by intrusive igneous rocks, as at Binny Quarry, Linlithgowshire, but also in a number of places where its origin is not evident, as in the Cornish and Derbyshire mining districts, and among the dark flagstones of Caithness and Orkney, which are laden with fossil fishes. At Seyssel (Département de l'Ain) it forms a deposit 2500 feet long and 800 feet broad, which yields 1500 tons annually. It exudes in a liquid form from the ground round the borders of the Dead Sea. In Trinidad it forms a lake 1½ mile in circumference, which is cool and solid near the shore, but increases in temperature and softness towards the centre. Uintaite is the name given to a brilliant black, brittle, tar-like variety of asphalt which, with its allied hydrocarbons, Wurtzilite, Elaterite, Ozocerite, and Maltha, is spread over a wide area in Eastern Utah, where it occurs as veins in sandstones, shales, and limestones, having evidently risen from below under considerable pressure so as to fill cracks in the strata and impregnate their substance.[1]

**Graphite.**—This mineral occurs in masses of sufficient size and importance to deserve a place in the enumeration of carbonaceous rocks. Its mineralogical characters have already (p. 92) been given. It occurs in distinct lenticular beds, and also diffused in minute scales, through slates, schists, and limestones of the older geological formations, as in Cumberland, Scotland, Canada, and Bohemia. In branching veins through granulites and other igneous rocks, it forms the most important mineral product of Ceylon.[2] The mode of origin of this rock is somewhat obscure. In certain cases, as where it has been found at New Cumnock in Ayrshire to have resulted from the intrusion of basalt into a coal-seam, it has obviously been formed from the alteration of vegetable material. But in the numerous cases where it runs in streaks and veins through igneous rocks, such an origin can hardly be conceived. It is then more probably due to the uprise of hydrocarbons from below, probably in a liquid, possibly gaseous condition, and to the final elimination of the hydrogen and isolation of the carbon. (Pp. 86, 185, 318, 357.)

6. Ferruginous.—The decomposition of vegetable matter in marshy places and shallow lakes gives rise to certain organic acids, which, together with the carbonic acid so generally also present, decompose the ferruginous minerals of rocks and carry away soluble salts of iron. Exposure to the air leads to the rapid decomposition and oxidation of those solutions, which consequently give rise to precipitates, consisting partly of insoluble basic salts and partly of the hydrated ferric oxide. These precipitates, mingled with clay, sand, or other mechanical impurity, and also with dead and decaying organisms, form deposits of iron-ore. Operations of this kind appear to have been in progress from a remote geological antiquity. Hence ironstones with traces of associated organic remains belong to many different geological formations, and are being formed still.[3] As already remarked, not only iron but also alumina appears to be abstracted from silicates by acidulous water and deposited as hydrate, as in the frequent association of limonite and bauxite deposits.

[1] G. H. Eldridge, *op. cit.*

[2] A. M. Ferguson, *Journ. Roy. Asiat. Soc.*, Ceylon Branch, vol. ix. (1885), No. 31, pp. 171-266. J. Walther, *Z. D. G. G.* xli. (1889), p. 359. M. Diersche, *Jahrb. K. K. Geol. Reichsanst*, xlviii. (1898), p. 231. A. K. Coomára-Swamy, *Q. J. G. S.* lvi. (1900), p. 609.

[3] See Senft's work already (p. 182) cited, p. 168; also *postea*, Book III. Part II. Sect. iii.

**Bog Iron-Ore** (Lake-ore, minerai des marais, Sumpferz)—a dark-brown to black, earthy, but sometimes compact mixture of hydrated peroxide of iron, phosphate of iron, and hydrated oxide of manganese, frequently with clay, sand, and organic matter. An ordinary specimen yielded peroxide of iron, 62·59 ; oxide of manganese, 8·52 ; sand, 11·37 ; phosphoric acid, 1·50 ; sulphuric acid, traces ; water and organic matter, 16·02=100·00. Bog iron-ore may either be formed *in situ* from still water, or may be laid down by currents in lakes. Of the former mode of formation, a familiar illustration is furnished by the "moor-band pan" or hard ferruginous crust, which in boggy places and on some ill-drained land, forms at the bottom of the soil, on the top of a stiff and tolerably impervious subsoil. Abundant bog-iron or lake-ore is obtained from the bottoms of some lakes in Norway and Sweden. It forms everywhere on the shallower slopes near banks of reeds, where there is no strong current of water, occurring in granular concretions (Bohnerz) that vary from the size of grains of coarse gunpowder up to nodules 6 inches in diameter, and forming layers 10 to 200 yards long, 5 to 15 yards broad, and 8 to 30 inches thick. These deposits are worked during winter by inserting perforated iron shovels through holes cut in the ice ; and so rapidly do they accumulate, that instances are known where, after having been completely removed, the ore at the end of twenty-six years was found to have gathered again to a thickness of several inches. A layer of loose earthy ochre 10 feet thick is believed to have formed in 600 years on the floor of the Lake Tisken near the old copper mine of Falun in Sweden.[1] According to Ehrenberg, the formation of bog-ore is due, not merely to the chemical actions arising from the decay of organic matter, but to a power possessed by diatoms of separating iron from water and depositing it as hydrous peroxide within their siliceous framework.

**Aluminous Yellow Iron-Ore** is closely related to the foregoing. It is a mixture of yellow or pale brown, hydrated peroxide of iron with clay and sand, sometimes with silicate of iron, hydrated oxide of manganese, and carbonate of lime, and occurs in dull, usually pulverulent grains and nodules. Occasionally these nodules may be observed to consist of a shell of harder material, within which the yellow oxide becomes progressively softer towards the centre, which is sometimes quite empty. Such concretions are known as Ætites or Eagle-stones. This ore occurs in the Coal-measures of Saxony and Silesia, also in the Harz, Baden, Bavaria, &c., and among the Jurassic rocks in England.

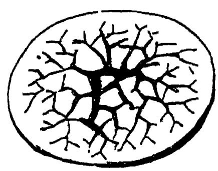

Fig. 25.—Septarian Nodule of Clay-ironstone.

**Clay-Ironstone** has been already (p. 107) referred to. It occurs abundantly in nodules and beds in the Carboniferous system in most parts of Europe. The nodules (Sphærosiderite) are generally oval and flattened in form, varying in size from a small bean up to concretions a foot or more in diameter, and with an internal system of radiating cracks, often filled with calcite (Fig. 25). In many cases, they contain in the centre some organic substance, such as a coprolite, fern, cone, shell, or fish, that has served as a surface round which the iron in the water and in the surrounding mud could be precipitated. Seams of clay-ironstone vary in thickness from mere paper-like partings up to beds several feet deep. The Cleveland seam in the middle Lias of Yorkshire is about 20 feet thick. In the Carboniferous system of Scotland certain seams known as *Blackband* contain from 10 to 52 per cent of coaly matter, and admit of being calcined with the addition of little or no fuel. They are sometimes crowded with organic remains, especially lamellibranchs (*Anthracosia, Anthracomya*, &c.) and fishes (*Rhizodus, Megalichthys*, &c.).

A microscopic examination of some ironstones reveals a very perfect oolitic structure,

[1] A. F. Thoreld, *Geol. Fören. Förhand. Stockholm*, iii. p. 20. A. W. Cronquist, *op. cit.* v. p. 402 ; H. Sjögren, *op. cit.* xiii. p. 373. See *postea*, Book III. Part II. Sect. ii. § 4, and Sect. iii. § 3.

showing that the iron has either replaced an original calcareous oolite or has been precipitated in water having such a gentle movement as to keep the granules quietly rolling along, while their successive concentric layers of carbonate were being deposited (Eisenoolith, Eisenrogenstein). Mr. Sorby has observed in the Cleveland ironstones an abnormal form of oolitic structure, and remarks that one specimen bore evidence that the iron, mostly in the form of small crystals of the carbonate, had been introduced subsequently to the formation of the rock, as it had replaced some of the aragonite of the enclosed shells.[1]

The subjoined analyses show the composition of some varieties of clay-ironstones.[2]

| | Clay iron-ore (Coal-measures). Yorkshire. | Black Band (Carboniferous), Scotland. | Cleveland ore (Lias), Yorkshire. |
|---|---|---|---|
| Protoxide of manganese | 1·45 | 2·72 | 2·86 |
| Protoxide of iron | 36·14 | 40·77 | 43·02 |
| Peroxide of iron | 1·38 | ... | 0·40 |
| Alumina | 6·74 | .. | 5·87 |
| Lime | 2·70 | 0·90 | 5·14 (zinc) |
| Magnesia | 2·17 | 0·72 | 5·21 |
| Potash | 0·65 | ... | ... |
| Silica | 17·37 | 10·10 | 7·17 |
| Carbonic acid | 26·57 | 26·41 | 25·50 |
| Phosphoric acid | 0·34 | ... | 1·81 |
| Sulphuric acid | trace | ... | ... |
| Iron pyrites | 0·10 | .. | .. |
| Water | 1·77 | 1·0 | 3·48 |
| Organic matter | 2·40 | 17·38 | 0·15 |
| | 99·78 | 100·00 | 100·61 |
| Percentage of iron | 29·12 | 34·60 | 5·46 |

B. Crystalline, including Rocks formed from Chemical Precipitation.

This division consists mainly of chemical deposits, but includes also some which, originally formed of organic calcareous débris, have acquired a crystalline structure. The rocks included in it occur as laminæ and beds, usually intercalated among clastic formations, such as sandstone and shale. Sometimes they attain a thickness of many thousand feet, with hardly any interstratification of mechanically derived sediment. They are being formed abundantly at the present time by mineral springs and on the floor of inland seas; while on the bottom of lakes and of the main ocean, calcareous organic accumulations are in progress, which will doubtless eventually acquire a thoroughly crystalline structure like that of many limestones.

**Ice.**—So large an area of the earth's surface is covered with ice, that this substance deserves notice among geological formations. Ice is commonly and conveniently classified in two divisions, snow-ice and water-ice, according as it results from the compression and alternate melting and freezing of fallen snow, or from the freezing of the surface or bottom of sheets of water (see Book III. Part II. Sect. ii. § 5).

[1] Address to Geol. Soc., February 1879.

[2] See Percy's 'Metallurgy,' vol. ii. Bischof, 'Chem. und Phys. Geol.' supp. (1871), p. 65.

Snow-ice is of two kinds. 1st, Fallen snow on mountain slopes above the snow-line gradually assumes a granular structure. The little crystalline needles and stars of ice[1] are melted and frozen into rounded granules which form a more or less compact mass known in Switzerland as *Névé* or *Firn*. 2nd, When the granular névé slowly slides down into the valleys, it acquires a more compact crystalline structure and becomes *glacier-ice*. According to the researches of F. Klocke, glacier-ice is, throughout its mass, an irregular aggregate of distinct crystalline grains, the boundaries of which form the minute capillary fissures so often described.[2] Its structure thus closely corresponds to that of marble (p. 192). Glacier-ice in small fragments is white or colourless, and often shows innumerable fine bubbles of air, sometimes also fine particles of mud. In larger masses, it has a blue or green-blue tint, and displays a veined structure, consisting of parallel vertical veinings of white ice full of air-bubbles, and of blue clear ice without air-bubbles. Snow-ice is formed above the snow-line, but may descend in glaciers far below it. It covers large areas of the more lofty mountains of the globe, even in tropical regions. Towards the poles it descends to the sea, where large pieces break off and float away as icebergs.

Water-ice is formed, 1st, by the freezing of the surface of fresh water (river-ice, lake-ice), or of the sea (ice-foot, floe-ice, pack-ice); this is a compact, clear, white or greenish ice. 2nd, by the freezing of the layer of water lying on the bottom of rivers, or the sea (bottom-ice, ground-ice, anchor-ice); this variety is more spongy, and often encloses mud, sand and stones.[3]

**Rock-Salt** (Sel gemme, Steinsalz, p. 108) occurs in layers or beds from less than an inch to many hundred feet in thickness. The salt deposits at Stassfurt, for example, are 1197 feet thick, of which the lowest beds comprise 685 feet of pure rock-salt, with thin layers of anhydrite ¼-inch thick dividing the salt at intervals of from one to eight inches. Still more massive are the accumulations of Sperenberg near Berlin, which have been bored to a depth of 4200 feet, and those of Wieliczka in Gallicia, which are here and there more than 4600 feet thick.

The more insoluble salts (notably gypsum or anhydrite) are apt to appear in the lower parts of a saliferous series. When purest, rock-salt is clear and colourless, but usually is coloured red (peroxide of iron), sometimes green or blue (chloride or silicate of copper). It varies in structure, being sometimes beautifully crystalline and giving a cubical cleavage; laminated, granular, or less frequently fibrous. It usually contains some admixture of clay, sand, anhydrite, bitumen, &c., and is often mixed with chlorides of magnesium, calcium, &c. In some places it is full of vesicles (not infrequently of cubic form) containing saline water; or it abounds with minute cavities filled with hydrogen, nitrogen, carbon-dioxide, or with some hydrocarbon gas. Occasionally remains of minute forms of vegetable and animal life, bituminous wood, corals, shells, crustaceans, and fish teeth are met with in it. Owing to its ready solubility, it is not found at the surface in most climates. It has been formed by the evaporation of very saline water in enclosed basins—a process going on now in many

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1 The student interested in the various crystallographic forms of snow-flakes will find a fine series of illustrations from photographs taken by Nordenskjöld, and published in different scientific journals in 1893, *Geol. För. Förhandl.*, Stockholm, xv. pp. 145-158; *Bull. Soc. Min. France*, xvi. p. 59; *Nature*, xlviii. p. 592. Another series of good reproductions from photographs after nature, taken by W. A. Bentley, is given in *Nature*, lxv. (1902), p. 284.

2 *Neues Jahrb.* i. (1881), p. 23. See also Mr. M'Connel, *Proc. Roy. Soc.* xlviii. (1890), p. 259; xlix. (1891), p. 323. Grad and Dupré (*Ann. Club Alp. Franc.* 1874) show how the characteristic structure of glacier-ice may be revealed by allowing coloured solutions to permeate it.

3 On the properties of ice, with some interesting geological bearings, see O. Pettersson, 'Vega-Expeditionens Vetenskapliga Iakttagelser,' ii. p. 249, Stockholm, 1883.

salt-lakes (Great Salt Lake of Utah, Dead Sea), and on the surface of some deserts (Kirgis Steppe). In different parts of the world, deposits of salt have probably always been in progress from very early geological times. Saliferous formations of Tertiary and Secondary age are abundant in Europe, while in America they occur even in rocks as old as the Upper Silurian period, and among the Punjab Hills in still more ancient strata.[1] (Book III. Part II. Sect. ii. § 4.)

In the deposits where rock-salt occurs other soluble salts may be met with in smaller quantity, which have likewise been derived from the evaporation of saline waters. Among these is Carnallite (p. 108)—a chloride of potassium and magnesium ($KCl$ 26·8, $MgCl_2$ 34·2, water 39), which attains a great development in the salt mines of Stassfurt, where it forms a bed 20 to 30 metres thick, overlying the rock-salt. It has been found in other old salt-deposits as well as among the "salterns" or "salines" along the Mediterranean coast, where the water of that inland sea is evaporated in the manufacture of salt. It so closely resembles rock-salt that it was formerly included with it. It is a valuable source for the manufacture of potash-salts. Kieserite—magnesium-sulphate ($MgSO_4$ 86·96, $H_2O$ 13·04) forms at Stassfurt alternating layers with rock-salt from an inch to a foot in thickness. Kainite—hydrous magnesium sulphate and potassium chloride (magnesium, 16·1; potassium, 15·7; chlorine, 14·3; sulphuric acid, 32·2; water, 21·7), occurs in yellowish or pale grey aggregates, sometimes of considerable thickness, and is distinguished from some of its associated salts by not deliquescing readily in the air. Sylvine—potassium-chloride (K 52·46, Cl 47·54), found crystallised in Kieserite.

**Natural Soda.**—From the drying up of alkaline lakes in different parts of the world extensive deposits of various alkaline salts have been formed, some of which have become of great economic value. "Natural soda" consists of a mixture of sodium carbonate and bicarbonate in varying proportions, with some impurities which are mainly chloride and sulphate of sodium. It is found in Hungary, Egypt, Armenia, and in various parts of North and South America. Urao is the name given to the natural carbonate of soda found in Venezuela ($Na_2O$ 41·22, $CO_2$ 39·00, $H_2O$ 18·80, impurities 0·98, total 100·00). The term Trona is applied to a native sesquicarbonate of sodium which contains a little sulphate of sodium. (Book III. Part II. Sect. ii. § 4.)

**Cryolite.**—A double fluoride of sodium and aluminium (Na 32·79, Al 12·85, Fl 54·36) occurs in considerable mass at Ivigtut, Arkutsfjord, in Greenland, where it appears as a large included aggregation in the granite, associated with quartz, galena, zinc-blende, pyrite and other minerals.

**Limestone.**—The general characters of this rock have already (p. 176) been enumerated in connection with those examples of it which have been formed by the aggregation of the remains of plants or animals. We have now to deal with limestones which have had a distinctly chemical origin, and also those which, though doubtless, in many cases, originally formed of organic débris, have lost their fragmental and have assumed instead a crystalline structure. From waters highly charged with carbonate of lime in solution precipitates of this substance form sheets of limestone. This process may take place in the sea, especially in shallow parts liable to concentration and evaporation. It occurs also in fresh waters, more particularly along the course of calcareous springs and streams. Such precipitates may at first be soft, white, and chalk-like, but eventually they harden, and may acquire a crystalline and even marble-like texture.

Compact, common Limestone—a fine-grained crystalline-granular aggregate, occurring in beds or laminæ interstratified with other aqueous deposits. When purest it is readily soluble in acid with effervescence, leaving little or no residue. Many varieties occur, to some of which separate names are given. *Hydraulic limestone* contains 10 per cent or more of silica (and usually alumina), and, when burnt and subsequently mixed

[1] On salt deposits of various ages, see A. C. Ramsay, *Brit. Assoc. Rep.* 1880, p. 10; also Index, *sub voc.* "Salt Deposits."

with water, forms a cement or mortar which has the property of "setting" or hardening under water. Limestones containing perhaps as much as 25 per cent of silica, alumina, iron, &c., that in themselves would be unsuitable for many of the ordinary purposes for which limestones are used, can be employed for making hydraulic mortar. These limestones occur in beds like those in the Lias of Lyme Regis, or in nodules like those of Sheppey, from which Roman cement is made. *Cementstone* is the name given to many pale dull ferruginous limestones, which contain an admixture of clay, and some of which can be profitably used for making hydraulic mortar or cement. *Fetid limestone* (*stinkstein*, *swinestone*) gives off a fetid smell when struck with a hammer. In some cases, the rock seems to have been deposited by volcanic springs containing decomposable sulphides as well as lime. In other instances, the odour may be connected with the decomposition of imbedded organic matter. In some quarries in the Carboniferous Limestone of Ireland, as mentioned by Jukes, the freshly-broken rock may be smelt at a distance of a hundred yards when the men are at work, and occasionally the stench becomes so strong that the workmen are sickened by it, and require to leave off work for a time. *Cornstone* is an arenaceous or siliceous limestone particularly characteristic of some of the Palæozoic Red Sandstone formations. *Rottenstone* is a decomposed siliceous limestone from which most or all of the lime has been removed, leaving a siliceous skeleton of the rock. A similar decomposition takes place in some ferruginous limestones, with the result of leaving a yellow skeleton of ochre. Common limestone, having been deposited in water usually containing other substances in suspension or solution, is almost always mixed with impurities, and where the mixture is sufficiently distinct it receives a special name, such as siliceous limestone, sandy limestone, argillaceous limestone, bituminous limestone, dolomitic limestone.

Travertine (calcareous tufa, calc-sinter) is the porous material deposited by calcareous springs, usually white or yellowish, varying in texture from a soft chalk-like or marly substance to a compact building-stone. (See *postea*, pp. 475, 605, 611, 613.) *Stalactite* is the name given to the calcareous pendant deposit formed on the roofs of limestone-caverns, vaults, bridges, &c.; while the water, from which the hanging lime-icicles are derived, drips to the floor, and on further evaporation there gives rise to the crust-like deposit known as *stalagmite*. Mr. Sorby has shown that in the calcareous deposits from fresh water there is a constant tendency towards the production of calcite crystals with the principal axis perpendicular to the surface of deposit. Where that surface is curved, there is a radiation or convergence of the fibre-like crystals, well seen in sections of stalactites and of some calcareous tufas (Fig. 109).

A variety of travertine formed both in caves and in the open air as a deposit from water, and distinguished by its laminated or clouded green, red, and brown colours, has long been used as an ornamental stone. It was obtained in ancient times from Algeria and Egypt, often in large and beautiful monoliths. It is known as oriental alabaster or onyx marble, and is found at Lake Oroomiah in Persia, in various parts of Italy and France, in large deposits in Arizona, California, Virginia, Colorado, Utah, and other parts of the United States, and in beautiful varieties in Mexico.[1]

Oolite—a limestone formed wholly or in part of more or less perfectly spherical grains, and having somewhat the aspect of fish-roe. Each grain consists of successive concentric shells of carbonate of lime, frequently with an internal radiating fibrous structure, which gives a black cross between crossed Nicols (Fig. 26). The calcareous material was deposited round some minute particle of sand or other foreign body which was kept in motion, so that all sides could in turn become encrusted. It is now known that minute algæ play an important part in some of these depositions, the carbonate being abstracted and precipitated round their filaments. Oolitic grains are now forming in this way at the springs of Carlsbad (Sprudelstein). They may also be produced

[1] G. P. Merrill, "The Onyx Marbles," *Rep. U. S. Nat. Museum*, Washington, 1895.

where gentle currents in lakes, or in partially enclosed areas of the sea, keep grains of sand or fragments of shells drifting along in water, which is so charged with lime as to be ready to deposit it upon any suitable surface. An oolitic limestone may contain much impurity. Where the calcareous granules are cemented in a somewhat argillaceous matrix the rock is known in Germany as Rogenstein. Where the individual grains of an oolitic limestone are as large as peas, the rock is called a pisolite (pea-grit). The granules sometimes consist of aragonite. Oolitic structure is found in limestones of all ages, from Palæozoic down to recent times.[1] Mr. E. Wethered has observed that many oolitic grains in the Palæozoic and Jurassic limestones of England show curious vermiform twistings in their outer concentric coats, which he regards as of organic origin, either plant or animal (*Girvanella*).[2] They appear to play the part of the algæ in the Sprudelstein and Tivoli travertine. In some instances oolites have had their calcareous matter replaced by carbonate or oxide of iron, so as to become oolitic ironstones.

Marble (granular limestone) — a crystalline-granular aggregate composed of crystalline calcite-granules of remarkably uniform size, each of which has its own independent twin lamellæ (often giving interference colours) and cleavage lines. This characteristic structure is well displayed when a thin slice of ordinary statuary marble

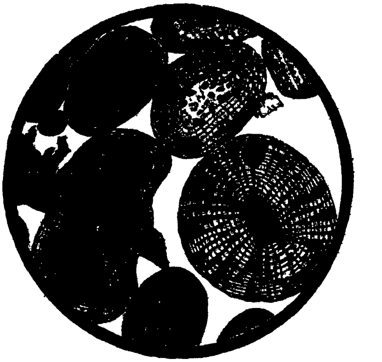

Fig. 26.—Microscopic Structure of Oolitic Limestone, after Sorby. (Magnified 30 Diameters.)

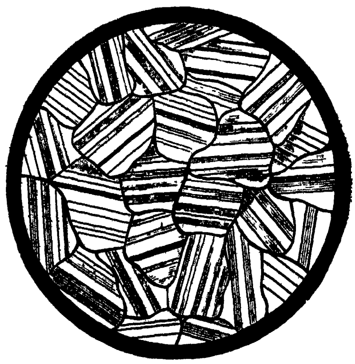

Fig. 27.—Microscopic (Saccharoid) Structure of Statuary Marble. (Magnified 50 Diameters.)

is placed under the microscope (Fig. 27). Typical marble is white, but the rock is also yellow, grey, blue, green, red, black, or streaked and mottled, as may be seen in the numerous kinds used for ornamental purposes. Its granular structure gives it a resemblance to loaf-sugar, whence the term "saccharoid" applied to it. Fine silvery scales of mica or talc may often be noticed even in the purest marble (*Cipollino*, p. 251). Some crystalline limestones associated with gneiss and schist are peculiarly rich in minerals —mica, garnet, tremolite, actinolite, anthophyllite, zoisite, vesuvianite, pyroxenes, and many other species occurring there often in great abundance. These inclusions can be isolated by dissolving the surrounding rock in acid (*ante*, p. 117).

Marble is a metamorphic rock, that is, one in which the calcium-carbonate, whether derived from an organic or inorganic source, has been entirely recrystallised *in situ*.

[1] Oolitic structure occurs even among the limestones of the Dalradian metamorphic series of Scotland (Islay), which may possibly be pre-Palæozoic.

[2] *Geol. Mag.* 1889, p. 196; *Q. J. G. S.* xlvi. (1890), p. 270; li. (1895), p. 196. Mr. C. Reid has suggested that the tubular bodies, called *Girvanella*, may be due to the deposit of lime round organic filaments (*Algæ*), like the calcareous incrustation formed round fibres of hemp in kettles and boilers.

In the course of this change the original clay, sand or other impurities of the rock have been also crystallised, and now appear as the crystalline silicates just referred to. Marble occurs in beds and large lenticular masses associated with crystalline schists on many different geological horizons. It is met with also as the result of the alteration of limestones by contact with masses of eruptive rock. In Canada it occurs of Laurentian; in Scotland of Cambrian; in Utah of Upper Carboniferous; in Southern Europe of Triassic, Jurassic, and Cretaceous age.[1]

**Dolomite** (Magnesian Limestone) consists typically of a yellow or white, crystalline, massive aggregate of the mineral dolomite; but the relative proportions of the calcium and magnesium-carbonates vary indefinitely, so that every gradation can be found, from pure limestone without magnesium-carbonate up to pure dolomite containing 45·65 per cent of that carbonate.[2] Ferrous carbonate is also of common occurrence in this rock. The texture of dolomite is usually distinctly crystalline, the individual crystals being occasionally so loosely held together that the rock readily crumbles into a crystalline sand. A fissured cavernous structure apparently due to a process of contraction during the process of "*dolomitisation*" (p. 426), is of common occurrence: even in compact varieties, cellular spaces occur, lined with crystallised dolomite (Rauchwacke), the crystals of which are often hollow and sometimes enclose a kernel of calcite. Other varieties are built up of spherical, botryoidal and irregularly-shaped concretionary masses. Dolomite, in its more typical forms, is distinguishable from limestone by its greater hardness (3·5–4·5) higher specific gravity (2·8–2·95), and much less easy solubility in acid. It occurs sometimes in beds of original deposit, associated with gypsum, rock-salt and other results of the evaporation of saturated saline waters; it is also found replacing what was once ordinary limestone. The process by which carbonate of lime is replaced by carbonate of magnesia, is referred to in Book III. Part. I. Sect. iv. § 2.[3] Dolomite sometimes forms picturesque mountain masses, as in the Dolomite Mountains of the Eastern Alps.

**Gypsum**—a fine-granular to compact, sometimes fibrous or sparry aggregate of the mineral gypsum, having a hardness of only 1·5–2 (therefore scratched with the nail), and a specific gravity of about 2·32; unaffected by acids and hence readily distinguishable from limestone, which it occasionally resembles. It is normally white, but may be coloured grey or brown by an admixture of clay or bitumen, or yellow and red by being stained with iron-oxide. It occurs in beds, lenticular intercalations and strings, usually associated with beds of red clay, rock-salt, or anhydrite, in formations of many various geological periods from Silurian (New York) down to recent times. The Triassic gypsum deposits of Thuringia, Hanover and the Harz have long been famous. One of them runs along the south flank of the Harz Mountains as a great band six miles long and reaching a height of sometimes 430 feet. The compact massive variety known as Alabaster has long been employed for ornamental purposes, though its softness limits its usefulness. It is also largely consumed for the manufacture of "Plaster of Paris."

Gypsum furnishes a good illustration of the many different ways in which some mineral substances can originate. Thus it may be produced, 1st, as a chemical

[1] An important memoir on the marbles of Norway, by Professor J. H. L. Vogt, will be found in *Norges Geol. Undersögelse*, No. 22 (1897). It discusses the geology, chemistry, mineralogy and structure of marble, together with its most important characters from an industrial point of view. See also his paper, "Der Marmor in Bezug auf seine Geologie, Structur und seine mechanische Eigenschaften," *Zeitsch. pract. Geol.* 1898, pp. 4, 43.

[2] On the origin of Dolomite see Klement, *Bull. Soc. Belge Géol.* ix. (1895), pp. 3-23; J. J. H. Teall, *Geol. Mag.* 1895, p. 329. See also the memoir by Vogt cited above.

[3] On the mineralogical nature of dolomite see O. Meyer, *Z. D. G. G.* xxxi. p. 445; Loretz, *op. cit.* xxx. p. 387; xxxi. p. 756. Renard, *Bull. Acad. Roy. Belg.* xlvii. (1879), No. 5, and the paper of Dr. Klement, cited in the previous note.

precipitate from solution in water, as when sea-water is evaporated ; 2nd, through the decomposition of sulphides and the action of the resultant sulphuric acid upon limestone ; 3rd, through the mutual decomposition of carbonate of lime and sulphates of iron, copper, magnesia, &c. ; 4th, through the hydration of anhydrite ; 5th, through the action of the sulphurous vapours and solutions of volcanic orifices upon limestone and calcareous rocks.[1] It is in the first of these ways that the thick beds of gypsum associated with rock-salt in many geological formations have been formed. The first mineral to appear in the evaporation of sea-water being gypsum, it has been precipitated on the floors of inland seas and saline lakes before the more soluble salts.[2]

**Anhydrite**,—the anhydrous variety of calcium-sulphate, occurs as a compact or granular, white, grey, bluish or reddish aggregate in saliferous deposits. It is less frequent than gypsum, from which it is distinguished by its much greater hardness (3–3·5), and into which it readily passes by taking up 0·2625 of its weight of water.[3] It often occurs in thin seams or partings in rock-salt : but it also forms large hill-like masses, of which the external parts have been converted into gypsum.

**Ironstone.**—Under this general term are included various iron-ores in which the peroxide, protoxide, carbonate, &c., are mingled with clay and other impurities. They have generally been deposited as chemical precipitates on the bottoms of lakes, under marshy ground, or within fissures and cavities of rocks. Some iron-ores are associated with schistose and massive rocks ; others are found with sandstones, shales, limestones and coals ; while some occur in the form of mineral veins. Those which have resulted from the co-operation of organic agencies are described at pp. 186, 612, 628.

Hæmatite (red iron-ore), a compact, fine-grained, earthy, or fibrous rock of a blood-red to brown-red colour, but where most crystalline, steel-grey and splendent, with a distinct cherry-red streak. Consists of anhydrous ferric oxide, but usually is mixed with clay, sand or other ingredient, in such varying proportions as to pass, by insensible gradations, into ferruginous clays, sands, quartz or jasper. Occurs as beds, huge concretionary masses and veins traversing crystalline rocks ; sometimes, as in Westmoreland, filling up cavernous spaces in limestone. Is found occasionally in beds of an oolitic structure among stratified formations. As already stated (pp. 177, 187), probably most of the oolitic or pisolitic ironstones have resulted from the conversion of original grains of calcite in ordinary oolites into carbonate of iron, which on oxidation has become magnetite hæmatite or limonite.

Limonite (brown iron-ore), an earthy or ochreous, compact, fine-grained or fibrous rock, of an ochre-yellow to a dark-brown colour, distinguishable from hæmatite by being hydrous and giving a yellow streak. Occurs in beds and veins, sometimes as the result of the oxidation of ferrous carbonate ; abundant on the floors of some lakes ; commonly found under marshy soil where it forms a hard brown crust upon the impervious subsoil (*bog-iron-ore*). Found likewise in oolitic concretions sometimes as large as walnuts, consisting of concentric layers of impure limonite with sand and clay (*Bohnerz*). (See p. 187 and Book III. Part II. Sect. iii. § 3.)

Spathic Iron-ore, a coarse or fine crystalline or dull compact aggregate of the mineral siderite or ferrous carbonate, usually with carbonates of calcium, manganese and magnesium ; has a prevalent yellowish or brownish colour, and when fresh, its rhombohedral cleavage-faces show a pearly lustre, which soon disappears as the surface is oxidized into limonite or hæmatite. Occurs in beds and veins, especially among older

[1] Roth. 'Chem. Geol.' i. p 553.

[2] For an elaborate account of the crystallisation of gypsum directly from the water of lagoons and as a secondary product from the reaction resulting from the decomposition of iron sulphide in rocks containing lime, see the memoir by Prof. Lacroix, 'Le Gypse de Paris et les Minéraux qui l'accompagnent,' *Nouv. Arch. Museum*, Paris, 1897.

[3] See G. Rose on formation of this rock in presence of a solution of chloride of sodium, *Neues Jahrb.* 1871, p. 932. Also Bischof, 'Chem. und Phys. Geol.' Suppl. (1871), p. 188.

geological formations. The colossal Erzberg at Eisenerz in Styria, which rises 2600 feet above the valley, consists almost wholly of siderite, belonging to the Silurian system.[1]

Clay-ironstone (Sphærosiderite), a dull brown or black, compact form of siderite, with a variable mixture of clay, and usually also of organic matter. Occurs in the Carboniferous and other formations, in the form either of nodules, where it has usually been deposited round some organic centre, or of beds interstratified with shales and coals. It is more properly described at p. 187, with the organically derived rocks.

Magnetic iron-ore, a granular to compact aggregate of magnetite, of a black colour and streak, more or less perfect metallic lustre, and strong magnetism. Commonly contains admixtures of other minerals, notably of hæmatite, chrome-iron, titanic-iron, pyrites, chlorite, quartz, hornblende, garnet, epidote, felspar. Occurs in beds and enormous lenticular masses (Stöcke) among crystalline schists; likewise in segregation-veins of gabbros and other eruptive rocks; also occasionally in an oolitic form (probably as a pseudomorph after an original calcareous oolite) among Palæozoic rocks, as in the so-called "pisolitic iron-ore" of North Wales. Among the Scandinavian gneisses lies the iron mountain of Gellivara in Lulea-Lappmark, 17,000 feet long, 8500 feet broad, and 525 feet high.

**Siliceous Sinter** (Geyserite, Kieselsinter), the siliceous deposit made by hot springs, including varieties that are crumbling and earthy, compact and flinty, finely laminated and shaly, sometimes dull and opaque, sometimes translucent, with pearly or waxy lustre, and with chalcedonic alterations in the older parts. The deposit may occur as an incrustation round the orifices of eruption, rising into dome-shaped, botryoidal, coralloid, or columnar elevations, or investing leaves and stems of plants, shells, insects, &c., or hanging in pendant stalactites from cavernous spaces which are from time to time reached by the hot water. When purest, it is of snowy whiteness, but is often tinted yellow or flesh colour. It consists of silica 84 to 91 per cent, with small proportions of alumina, ferric oxide, lime, magnesia and alkali, and from 5 to 8 per cent of water. (See Book III. Part II. Sect. iii. § 3, p. 609.)

**Flint** and Chert have been already described among the rocks of organic origin (pp. 179, 180). **Hornstone**, an excessively compact siliceous rock, usually of some dull dark tint, occurs in nodular masses or irregular bands and veins. The name has sometimes been applied to fine flinty forms of felsite. **Vein-Quartz** may be alluded to here as a substance which sometimes occurs in large masses. It is a massive form of quartz found filling veins (sometimes many yards broad) in crystalline and clastic rocks; more especially in metamorphic areas. (See Quartzite, p. 249.)

## II. ERUPTIVE—IGNEOUS—MASSIVE—UNSTRATIFIED.

Almost all the members of this important subdivision have been produced from within the crust of the earth, in a molten condition. The circumstances under which they have come to occupy their present positions will be discussed in later parts of this work. We are here concerned with their characters as masses of mineral matter. Great divergence of opinion still exists as to the best system of classification to be followed in regard to them. As Mr. Teall has pointed out, they possess seven groups of characters which may be used as bases for schemes of arrangement. 1st, chemical composition; 2nd, mineralogical composition; 3rd, texture; 4th, mode of occurrence in the field, as in their relation to surrounding rocks, structural features, &c.; 5th, origin; 6th, geological age (distribution in time); 7th, locality (dis-

[1] Zirkel, 'Lehrb.' iii. p. 581.

tribution in space).[1] In any system of classification it must obviously be desirable to found it upon characters that are easily ascertained and about which, when so ascertained, there can be no room for dispute. Tried by this standard some of the seven groups of characters here enumerated must clearly be set aside as insufficient of themselves to form the basis of a satisfactory arrangement, though they may be made useful in subordinate grouping. Thus the Distribution of Rocks in Space is manifestly inadequate for the purpose, for though there are petrographical provinces, each presenting a more or less distinct assemblage of rocks with certain characteristic relations between them, the rocks are in many cases not to be distinguished by any essential feature from similar rocks in other provinces. Nor is the question of Origin more available in dealing with the igneous rocks as a whole, being too vague in itself and our knowledge of the subject being often exceedingly limited.

A much better foundation for a scheme of classification is afforded by Texture, or the internal structure of rocks. Microscopic research having revealed the existence of three leading types of micro-structure—*Granular*, *Porphyritic* and *Glassy*, or *Holocrystalline*, *Hemicrystalline* and *Vitreous*, a threefold grouping of the igneous rocks has accordingly been made on this basis. Again, MM. Fouqué and Michel-Lévy, pointing out that most eruptive rocks are the result of successive stages of crystallisation, each recognisable by its own characters, show that two phases of consolidation are specially to be observed, the first (porphyritic) marked by the formation of large crystals (phenocrysts), which were often broken and corroded by mechanical and chemical action within the still unsolidified magma; the second by the formation of smaller crystals, crystallites, &c., which are moulded round the older series. In some rocks the former, in others the latter of these two phases is alone present.

Two leading types of structure are recognised by these authors among the Acid eruptive rocks. 1. Granitoid (Γ), where the constituents are of two epochs of consolidation, similar in character, and where neither amorphous magma nor crystallites are to be seen. This structure includes three varieties: (α) the *Granitic*, having crystals of approximately equal size, and where the quartz is moulded round the other constituents; (β) *Granulitic*, where the quartz tends to assume partially its crystallographic forms; (γ) *Pegmatoid*, where there has been a simultaneous crystallisation of the quartz and felspar in graphic form. 2. Porphyric (Π), where two epochs of consolidation are recognisable in distinct products, the second being finer than the first. Five varieties are distinguished: (α) *Microgranitic* (as under Γ); (β) *Microgranulitic*; (γ) *Micropegmatoid*; (φ) *Globular*, with radial spherulites impregnated with quartz oriented in one optical direction, the base being often composed of irregular grains of quartz and felspar; (π) *Petrosiliceous*; hemi-crystalline to vitreous, with lines of spherulites. The Basic eruptive rocks likewise display the same two structure-types, but with a difference. Thus: 1. Granitoid (Γ), having an entirely crystalline structure, which may be either (δ) *Granular*, where a felspar is moulded round the other elements which have crystallised in every direction; or (ω) *Ophitic*, where a bisilicate (pyroxene, amphibole) serves as a cement to the crystals of felspar or other constituents. 2. Trachytoid (Π), which may be entirely crystallised, as (δ) *Granular* (as under Γ), or (ω) *Ophitic*, or may range from crystalline, through hemi-crystalline to vitreous, and is then distinguished

[1] 'British Petrography,' p. 64.

as ($\mu$) *Microlitic*, where microlites have been developed, usually more or less linearly grouped as in flow-structure, with perlitic and variolitic varieties.[1]

Strong arguments have been adduced in favour of making the mode of occurrence of rocks in the field the main foundation of a classification of igneous rocks. If the wide range of diversity in composition and texture among those mineral masses were neglected such a geological arrangement might serve sufficiently the purposes of the field-geologist, though even he in a denuded region cannot always be sure of the real structure and mode of occurrence of some rocks which may have consolidated beneath as sills, or may have reached the surface as lavas. Some petrographers, however, recognising the right of the geologist to insist that in any system of arrangement the geological behaviour of the rocks shall be considered, have advocated the adoption of a geological grouping as the leading feature of their scheme. The most noteworthy effort of this kind has been made by Professor Rosenbusch, who, somewhat enlarging the time-honoured arrangement into plutonic and volcanic, groups the igneous rocks in three great sections: 1st, the deep-seated rocks (Tiefen-gesteine), which have consolidated as plutonic or intrusive masses far below the surface, and are distinguished by a hypidiomorphic granular structure; 2nd, dyke-rocks (Gang-gesteine), which may have been injected as dykes and veins at a less distance from the surface (hypabyssal), though some portions of them may come above ground in volcanic eruptions—they are marked by a panidiomorphic or porphyritic structure; and 3rd, the effusive or volcanic rocks (Erguss-gesteine), which have escaped to the surface and have there solidified—they possess a porphyritic structure. Each of these three great divisions is further separated into families, according to mineralogical composition, beginning with acid types and ending with the most basic. The distinguished Heidelberg professor, in thus endeavouring to reconcile the conflicting claims of the field-geologist and the mineralogical petrologist, deserves the thanks of both. But his scheme, though it looks logical and well considered, fails to satisfy the requirements of either school. The idea of arranging eruptive rocks in accordance with the condition under which they have solidified has of course been familiar to geologists for several generations. Deep-seated intrusions, with their apophyses and dykes have been recognised as generally, though not invariably, possessing characters different from those of lavas that have been poured out at the surface. But these characters, though well adapted for use among the several subdivisions of the classification, are insufficient in themselves to afford a starting-point for the whole scheme. We must remember that the masses of material which have reached the surface are the upward prolongations of masses that solidified below it, that they represent different

[1] Fouqué and Michel-Lévy, 'Minéralogie Micrographique,' p. 150; and Michel-Levy, 'Structure et Classification des Roches Éruptives,' 1889, pp. 29, 37. The last-named author has devised an ingenious system of notation, whereby the structure and composition of igneous rocks can be briefly described in definite symbols. The notation for Structure is by means of Greek letters (capital and small), as shown above. The symbols for Composition are given on p. 200.

portions of what was one continuous body, that we cannot always be sure whether what is now at the surface appeared there at first or has only been laid bare by denudation, and that we are still very ignorant of the conditions under which at different depths the molten magma would consolidate and of the corresponding textures which it would assume. It has been objected to Professor Rosenbusch's scheme that each division is made to include rocks which likewise come into the others, and to exclude rocks which it might properly comprise. Thus his division of the deep-seated rocks comprehends the granites, yet some granites have been demonstrated to be by no means deep-seated, but to have solidified not far below the surface, while other members of the division have risen in dykes and have actually consolidated above the surface. Again his dyke-rocks have not all been found in dykes, nor do they include all the rocks that have been so found. His effusive rocks in like manner are made to comprise rocks which have certainly consolidated at great depths, as well as many others which occur in veins and dykes. Useful therefore as the arrangement may be as a convenient grouping in discussing the tectonic structure of a region, it is insufficient alike for the petrographer and the geologist, who require a more precise and easily applied scheme which shall not involve hypothetical assumption nor contradict experience in the field.

The geological age of igneous rocks has by other petrographers been used as a general ground of classification. Long before petrography had reached its modern development, and when the intimate mineralogical composition of rocks was most imperfectly known, the Wernerian doctrine still survived that there had been a progressive change in the characters of crystalline rocks during the course of geological time. It was a favourite belief that those igneous masses which were erupted prior to the Secondary periods differed materially from those that appeared after them in Tertiary and recent time. The one series was classed as "older" and the other as "younger." The idea still to some extent survives in Professor Zirkel's classification and in that of Professor Rosenbusch, wherein the older or palæo-volcanic are separated from the younger or neo-volcanic effusive rocks. It has been elaborated in great detail by M. Michel-Lévy, who maintains that the same volcanic types have been reproduced nearly in the same order in the two series, though basic rocks, often with vitreous characters, rather predominate in the later.[1] It must, indeed, be admitted that certain broad distinctions between the older and the later eruptive rocks have been well ascertained, and appear to hold generally over the world. Among these distinctions may be mentioned as more characteristic of the Palæozoic rocks the presence of microcline, turbid orthoclase in Carlsbad twins, muscovite, enstatite, bronzite, diallage,

[1] See J. D. Dana, *Amer. J. Sci.* xvi. (1878), p. 336. Michel-Lévy, *Bull. Soc. Géol. France*, 3rd ser. iii. (1874), p. 199 ; vi. p. 173 ; *Ann. des Mines*, viii. (1875) ; 'Structures et Classification des Roches Éruptives,' 1889 ; "Classification des magmas des Roches Éruptives," *B. S. G. F.* xxv. (1897), pp. 326-377. Fouqué and Michel-Lévy, 'Minéralogie Microgr.' p. 150. Reyer, 'Physik der Eruptionen,' 1877, Part iii. opposes the adoption of relative age as a basis of classification.

tourmaline, anatase, rutile, cordierite, and in the younger rocks the presence of sanidine, tridymite, leucite, nosean, hauyne, and zeolites. Even where the same mineral occurs in both the older and newer series, it often presents a somewhat different aspect in each, as in the case of the plagioclase and augite, which in the younger series are distinguished by the occurrence in them of vitreous and gaseous inclusions which are rare or absent in those of the older series.[1] Throughout the younger eruptive rocks, the vitreous condition is much more frequent and perfectly developed than in the older group, where, on the other hand, the granitic structure is characteristically displayed. Still, to these rules so many exceptions occur that it may be doubted whether enough of positively ascertained data have been collected regarding the relative ages of eruptive rocks to warrant the adoption of any classification upon a chronological basis. There can be no doubt that, making due allowance for the alterations arising from permeation by meteoric water, there is no essential difference between some types of volcanic rock in Palæozoic and in recent times. The Carboniferous basalts and trachytes of Scotland, for example, present the closest resemblance to those of Tertiary age. Admitting, therefore, that certain broad distinctions can be made between many ancient and modern eruptive rocks, it seems nevertheless inexpedient, in the present state of our knowledge, to employ relative antiquity (which must be determined by a totally distinct branch of geological inquiry, and may be erroneously determined) as a basis of petrographical arrangement. Accordingly relative antiquity has long been abandoned by the geologists of Britain and America as affording any adequate ground for a classification of rocks.

The Composition of the igneous rocks, chemically and mineralogically, probably affords on the whole the best foundation on which to build a scheme for their classification. Nearly all of them consist of two or more minerals. Considered in the broadest sense from a chemical point of view, they may be described as mixtures, in different proportions, of silicates of alumina, magnesia, lime, potash and soda, usually with magnetic iron and phosphate of lime. In one series, the silicic acid has not been more than enough to combine with the different bases; in another, it occurs in excess as free quartz. Taking this feature as a basis of arrangement, some petrographers have proposed to divide the rocks into an acid group, including such rocks as granite, quartz-porphyry and rhyolite, where the percentage of silica ranges from 60 to 75 or more, a basic group, typified by such rocks as basalt, where the proportion of silica is only about 50 per cent or less, and an intermediate group represented by the andesites with a proportion of silica ranging between that of the other two groups.[2]

M. Michel-Lévy, whose notation expressive of the structure of igneous rocks has been already (p. 196) referred to, has also devised a system of symbols to denote the

[1] See J. Murray and A. Renard, *Proc. Roy. Soc. Edin.* xi. p. 669.

[2] See papers by Professor Rosenbusch, *Tschermak's Min. Mittheil.* xi. (1889), p. 144; *ibid.* xii. (1892), pp. 351-396, his 'Massige Gesteine' and the bibliography given on next page.

mineral composition of these rocks.[1] The initial letters of the minerals are selected, capitals being employed for the ferruginous series, and small letters for the colourless constituents, while those ingredients which are in such small quantity as to be, so to speak, accidental constituents are distinguished by italics. The symbols are ranged from left to right in their usual order of consolidation. The minerals of the first consolidation, in débris more or less resorbed, are marked by a line above their letters, those of the second consolidation by a line below their letters. The Greek letters indicating the structure are placed at the beginning. The following examples will show the application of the system:—

1. Granite, $\Gamma\alpha$ with contacts $\Pi\alpha\gamma$—$(F_{5\ \mathrm{to}\ 8})$ $(H_2P_2A_2\mathrm{M})$ $(\mathrm{t_1a_1a'_1\underline{a_3}})(\mathrm{q})$.
2. Gabbro, $\Gamma\omega$—$(F_{1,2,3,5,6})$ $(\overline{\mathrm{OH}_{1,2}A_3M})$ $(\mathrm{t}_{\underline{2},3})$ $(\underline{\mathrm{P}}_3)$.

The Granite (1) is a granitoid (Γ) rock with a granitic ($\alpha$) structure, and its margins show porphyric structures (Π), partly microgranitic ($\alpha$) and partly micropegmatoid ($\gamma$). It consists of the following minerals in their order of consolidation:—Apatite ($F_5$), zircon ($F_6$), sphene ($F_7$), and allanite ($F_8$), all in small amount as accessory but early constituents. Then come also in feeble quantity, bronzite ($H_2$), malacolite ($P_2$), and grey amphibole ($A_2$), with abundant black mica (M). To these minerals as products of the first consolidation must be added, as essential constituents, oligoclase ($\mathrm{t}_1$) and orthoclase ($\mathrm{a}_1$). The minerals of the later consolidation include some orthoclase, also albite ($\mathrm{a}_3$) and abundant quartz (q). The Gabbro (2) has a granitoid or holocrystalline structure (Γ), with an ophitic ($\omega$) arrangement of its minerals, which consist of a small proportion of magnetite ($F_1$), titanic iron ($F_2$), spinel ($F_3$), apatite ($F_5$), and zircon ($F_6$), abundant olivine (O) and hypersthene ($\mathrm{H}_1$) and bronzite ($\mathrm{H}_2$); a little brown hornblende ($A_3$) and black mica ($M$); a good deal of labrador and anorthite felspar ($\mathrm{t}_{2,3}$). In the second consolidation these felspars also appear together with much diallage ($\mathrm{P}_2$).

In the vast majority of igneous rocks, the chief silicate is a felspar—the number of rocks where the felspar is represented by another silicate (as leucite or nepheline) being comparatively few and unimportant. As the felspars group themselves into two divisions, the monoclinic or orthoclase, and the triclinic or plagioclase, the former with, on the whole, a preponderance of silica; and as these minerals occur under tolerably distinct and definite conditions, the felspar-bearing Massive rocks have sometimes been divided into two series: (1) the Orthoclase rocks, having orthoclase as their chief silicate, and often with free silica in excess, and (2) the Plagioclase rocks, where the chief silicate is some species of triclinic felspar. The former series corresponds generally to the acid group above mentioned, while the plagioclase rocks are intermediate and basic. It has been objected to this arrangement that the so-called plagioclase felspars are in reality very distinct minerals, with proportions of silica, ranging from 43 to 69 per cent; soda from 0 to 12; and lime from 0 to 20.[2] In addition to the felspar-rocks, those in which felspar is either wholly absent or sparingly present, and where the chief part in rock-making has been taken by nepheline, leucite, olivine or serpentine must make another family or series of groups.[3]

[1] 'Struct. et Classif. des Roches Érupt.' p. 37.

[2] Dana, *Amer. Journ. Sci.* 1878, p. 432. The modern methods of separating the felspars remove some of the difficulty above referred to.

[3] A large amount of writing has been devoted to the subject of the classification of the igneous rocks. In addition to the works of MM Fouqué, Michel-Lévy and Rosenbusch, already cited, the following deserve the attention of the student: Zirkel's 'Petrographie,'

In Professor Rosenbusch's scheme of classification the chemico-mineralogical characters of the igneous rocks are chosen as the basis of the grouping in each of his three great divisions. Thus he places together those rocks which are especially marked by the presence of an alkali felspar (orthoclase, microcline, anorthoclase, albite); the lime-soda felspar rocks form another series. There are likewise groups in which the place of the felspar is taken by leucite, by nepheline, or by melilite, and others in which no felspar or felspathoid mineral is present, but where the constitution is pyroxenic or peridotitic.

It must be confessed that up to the present time no such system of arrangement of rocks has been devised as will harmonise and satisfy the claims of the field-geologist, the petrographer and the chemist. In the following pages no attempt will be made to do more than place the rocks in a general progressive order from the most acid to the most basic. Where convenient, those having the same general characters or occurring in nature associated with each other will be grouped together in families. Thus in the first part of the list, rocks will be found in which the silica percentage is not less than 60 and may even exceed 80, the acid being in such excess as to have separated out as free quartz. The structure of these rocks ranges from the most coarsely crystalline-granular (granitic) through various stages of hemi-crystalline (porphyritic, trachytoid) to the most perfect glass (vitreous, as in obsidian). After these quartzose rocks comes a large series in which quartz is either absent or appears only in small quantity, the silica percentage ranging from 55 or less to 66. In this intermediate series a similar diversity of texture and structure may be traced. At the one end stand thoroughly crystalline granitoid rocks, such as many syenites, while at the other come various forms of volcanic glass, such as the pitchstones of the trachytes and andesites. Beyond these rocks we enter a third assemblage, distinguished by the dropping of its silica percentage generally below, and in the extreme forms considerably below, 50. These basic rocks display holo-crystalline granitoid forms and many successive variations of hemi-crystalline structure until they once more lead us to thorough volcanic glasses.

The petrographical nomenclature of the Eruptive Rocks is in no better plight than their classification. By the progress of investigation it has been more and more conclusively ascertained that the hard and fast lines once supposed to separate the various species of these rocks, and which were expressed by distinct names in the terminology, do not

i. pp. 636-842, especially from p. 829; Vogelsang, *Z. D. G. G.* xxiv. p. 507; Lossen, *ibid.* p. 782; O. Lang, *Tschermak's Mittheil.* xi. (1890), p. 467; Professor Bonney, Presidential Address to Geol. Soc. 1885; Brögger, 'Die Eruptivgesteine des Kristianiagebietes. I. Die Gesteine der Grorudit-Tinguait-Serie,' Christiania, 1894; J. P. Iddings, *Journ. Geol.* i. (1893), p. 833; vi. (1898), pp. 92, 219; Whitman Cross, *op. cit.* p. 79; and the important paper, x. 1902, p. 555, published while these pages are passing through the press; W. H. Hobbs, *op. cit.* viii. (1900), p. 1; J. E. Spurr, *Amer. Geol.* xxv. (1900), p. 210; F. Lœwinson-Lessing, *Congrès Géol. Internat.* St. Petersburg (1897), 'Mémoires," pp. 53-73, 193-464; J. Walther, *ibid.* p. 10; A. Osann, *Tschermak's Mittheil.* xix. (1900), pp. 351-469; xx. (1901), pp. 400-558; xxi. (1902), p. 365; A. Harker, *Science Progress*, iv. (1895-96), p. 469.

really exist in nature. It has been found that one rock graduates into another, and that the variations of their composition and structure are often to be traced rather to differences in the conditions under which they have consolidated than to any marked divergences in the original magma. Thus a body of acid rock, such as granite, may be found to merge insensibly into a peripheral basic envelope, including even such ultra-basic material as serpentine. There has been in large eruptive masses a complex process of differentiation whereby the initial constituents have separated more or less completely from each other, thus giving rise to widely diverse types of rock in what was originally one body of material. The nature and effects of this process can best be studied in large intrusive bosses, and will therefore be discussed in Book IV. Part VII. Sect. i. In the meantime it will be obvious that if such is the actual variable character of the igneous rocks we ought not to attempt in our terminology a rigidity which does not exist in nature, but should aim at keeping it elastic enough to include not only well-defined species but transitional forms, and to indicate as far as possible the actual petrographical relationships of the rocks.

The present nomenclature of the eruptive rocks is a curiously jumbled patch-work, which has grown up with the gradual increase of knowledge, but on no settled system or plan. Like the terminology of the stratified formations in geology, it reveals in its very names the successive stages of advancement through which the study of rocks has passed. Some of these names, such as Syenite and Basalt, go back to Roman times, and are to be found in Pliny's 'Natural History.' Others are adaptations of the popular names of the rocks in the districts where they were first studied, as Gabbro, Minette, Hälleflinta and Forellenstein. Some, again, date from the days before the rise of geology when the rocks were under the care of the mineralogists, who named them from some obvious external character, such as lustre (Perlite, Pitchstone); texture (Hornstone, Porphyry); colour (Melaphyre); sound emitted when struck (Clinkstone, Phonolite); roughness to the touch (Trachyte); indistinctness or deceptiveness of the constituent minerals (Aphanite, Dolerite); obviousness of these minerals (Diorite); arrangement of the minerals (Pegmatite). As more detailed examination of the rocks revealed some of their internal characters names expressive of these were applied to them, such as Tachylyte, Hyalomelane and Eurite, so called from their easy fusibility, and Pyromerid, from its partial fusibility. When they were found to be of very different ages terms were sometimes introduced to express relative antiquity, such as Proterobas, Palæopicrite, Palæodolerite. Eventually a preference came to be shown for geographical designations, generally marking the place where a rock was first recognised or where it was specially well developed; hence arose such names as Andesite, Vogesite, Predazzite, Tonalite. This practice has now become general, and has introduced into petrography many uncouth terms. From Norway we have received a host of new words, including Grorudite, Sölvsbergite, Tinguaite; from Western America comes the Absarokite-Shoshonite-Banakite series. As such names, though descriptive of typical localities and therefore of

value, give no information as to the nature of the mineral masses designated by them, some petrographers prefer to keep as far as possible the more generic names that can be retained and to add to them epithets that will differentiate the new species or varieties. This they usually achieve by prefixing the names of the distinctive mineral or minerals. When only one name is thus added the compound is easily spoken or written, as tourmaline-granite; but as the number increases this ease disappears. Thus we have mica-biotite-granite, mica-hornblende-quartz-syenite, nepheline-nosean-sodalite-phonolite—sesquipedalian designations against which the patience even of a geologist is inclined to rebel. It has been proposed, in order to obviate the objection to new geographical names and to the multiplication of such cumbrous epithets, to keep the name of the prevalent type as the family designation, prefixing to it such mineralogical or geographical terms as would denote the species or variety; thus dolerite, trachydolerite, biotite-trachydolerite.[1] But some of the combinations proposed are hardly less cumbrous and cacophonous than those which they are proposed to replace. One able petrographer has remarked that many, perhaps most of the names may be but temporary in their use, and that they will "fulfil their legitimate object of enabling us to comprise a given set of characters in one word, make our ideas of the various rock-types more clear and precise, and thus lead us towards the solution of that vexed question—a rational and generally accepted classification of rocks. . . . The needless names and types will be gradually discarded, and on what is left we may build a nomenclature of which the terms will be concordant both with each other and with the facts of nature, whenever the broad principle underlying the relationships of rocks shall have been discovered."[2] Let us hope that in the not distant future this happy consummation may be reached.

### i. Granite Family.

The rocks belonging to this family are mainly of plutonic origin; that is, they have been intruded into the terrestrial crust, often at great depths below the surface, and have been injected in fissures, forming there dykes and veins. They include the great bulk of the older eruptive rocks, but also masses of all ages, even down to Tertiary time. Some of the youngest of them are connected with volcanic action, as in the west of Scotland, where granites have risen through the sheets of basalt that were poured out at the surface after the Eocene period.

**Granite.**[3]—A thoroughly crystalline admixture of an alkali-felspar (usually orthoclase,

[1] H. S. Washington, *Journ. Geol.* v. (1897), pp. 360, 365; C. R. Van Hise, *op. cit.* vii. (1899), p. 686 *et seq.*

[2] H. S. Washington, *loc. cit.*

[3] The student will find an ample bibliography of granite in Zirkel's 'Lehrbuch,' ii. pp. 76-82, and in Rosenbusch's 'Mikroskop. Phys.' The British granites are described in Mr. Teall's 'British Petrography,' p. 313; those of Ireland by Haughton, *Q. J. G. S.* xii. (1856), p. 171; xiv. (1858), p. 300; xviii. (1862), p. 403; xx. pp. 116, 268; W. J. Sollas, *Trans. Roy. Irish Acad.* xxix. (1891), pp. 427-514; those of France (Brittany) by Barrois in a series of papers in the *Ann. Soc. Géol. Nord.* from 1884 onwards; (Flamanville and France generally) Michel-Lévy, *Bull. Cart. Géol.* No. 36 (1893); *Bull. S. G. F.*, 3rd ser. iii. p. 199; (Pyrenees) Lacroix, *Bull. Carte. Géol. France*, Nos. 64 and 71; United States, C. King, vol. i. of 'Explor. 40th Parallel,' p. 111; Zirkel, vol. vi. of same series; G. Hawes, 'Geology of New Hampshire,' iv. (1878), p. 190. A few other papers are cited on subsequent pages.

often microcline) and quartz, with a plagioclase lime-soda felspar and more or less magnesia-mica, sometimes potash-mica, and not infrequently hornblende. The two chief ingredients, quartz and felspar, form a granular aggregate in which the grains, seldom showing crystal forms, are of fairly equal size, and in which the other minerals are dispersed. Some varieties are so coarse as to present their quartz and felspar in lumps several inches in diameter. From this extreme every gradation may be traced to such an exceedingly fine texture as not to be separable by the naked eye into the different minerals. There is never any base or ground-mass between the minerals, granite being a typically holocrystalline rock (Figs. 14 and 28). Occasionally the orthoclase may be seen to present a crystal face to the quartz; much more rarely the quartz itself, which is generally in angular or irregular grains, shows its pyramidal terminations. The orthoclase is frequently flesh-coloured and always dull or milky. Intergrowths of the alkali felspar and albite give rise to the formation of *microperthite*. The plagioclase is usually oligoclase, and may be distinguished by its fine parallel striation on the basal cleavage plane.

Fig. 28.—Holocrystalline Structure of Granite (magnified).

As an example of the method referred to on p. 116 for isolating the mineral constituents of rocks reference may be made here to the highly interesting and instructive memoir by Professor Sollas on the Granites of Leinster.[1] By that method it was found possible to isolate and study the zircons, apatites, biotites, muscovites, felspars and quartz. Their crystallographic forms could be measured and their internal zones of growth could be examined. Of the felspars the soda-lime species were found to be most abundant, varying from oligoclase to albite. Microline was more plentiful than orthoclase, the latter being absent in much of the granite of the district.

Many granites contain irregularly shaped cavities (miarolitic structure), in which the component minerals have had room to crystallise in their proper forms, and where beautifully terminated crystals of quartz and felspar may be observed. It is in these places also that the accessory minerals (beryl, topaz, tourmaline, garnet, orthite, zircon and many others) are found in their best forms. Not improbably these cavities were somewhat analogous to the steam holes of amygdaloids, but were filled with water or vapour of water at a high temperature and under great pressure, so that the constituents could crystallise under the most favourable conditions. Among the component minerals of granite, the quartz presents special interest under the microscope. It is often found to be full of cavities containing liquid, sometimes in such numbers as to amount to a thousand millions in a cubic inch and to give a milky turbid aspect to the mineral. The liquid in these cavities appears usually to be water, either pure or containing saline solutions, sometimes liquid carbon-dioxide (p. 143).

Varieties of granite have been distinguished, according to the prevalence of some other mineral besides the fundamental quartz and felspars. Thus under the name **Muscovite-granite** are comprised those which, besides the quartz and felspars, contain potash-mica. **Biotite-granite** (**Granitite**) includes those which have magnesia-mica, and may or may not contain also a little hornblende. Some granites have both muscovite and biotite-mica. **Hornblende-granite** comprehends those varieties in which besides the quartz and felspar, hornblende is also present, while when biotite is also there in notable quantity, the compound is termed hornblende-biotite-granite or hornblende-granitite. Of this last-named variety is the well-

[1] *Trans. Roy. Irish Acad.* xxix. (1891), p. 437.

known *Rapakiwi* of Finland, so much employed in Northern Russia, which contains egg-shaped pieces of orthoclase dispersed through a coarse-grained matrix. Still more widely familiar is the rock which occurs at Syene in Upper Egypt, whence it was obtained anciently in large blocks for obelisks and other architectural works, and of which well-known Egyptian monoliths are made. It was called by Pliny "Syenite,"—a name adopted by Werner as a general designation for hornblendic granites without quartz. The rock of Syene is really a hornblende-biotite-granite. In Tourmaline-granite tourmaline takes the part of the mica or hornblende. Augite-granite contains augite and black mica.[1] Aplite (Halbgranit, Granitell) is a granite that contains hardly any silvery mica and is made wholly or almost wholly of a finely granular or saccharoid aggregate of quartz and orthoclase with a little plagioclase; it is found chiefly in veins. Protogine-granite or Alpine granite, a rock that enters largely into the structure of the Alps, is distinguished by the presence of a light greenish chloritic or sericitic mineral, which when abundant gives it a somewhat schistose aspect.

Under the name *Granulite* M. Michel-Lévy includes certain fine-grained granites with white mica, which to the naked eye appear to be composed entirely of felspar and quartz, or of felspar alone, though both mica and quartz appear in abundance when the rocks are microscopically examined. He includes in this category most of the rocks of the Alps described as "protogine."[2]

Fig. 29.—Vein of finer grain (aplite) traversing a coarsely crystalline Granite.

Most large masses of granite present differences of texture and structure in different parts of their area. Some of these variations depend on the relation of the mass to the surrounding rocks (see *postea*, p. 724). Others may occur in any portion of a granite boss, and have been produced by the circumstances in which the mass consolidated. Some granites are marked by the peculiar grouping of their component minerals, others by the occurrence of the cavities above referred to, where the minerals have had room to assume sharply defined crystalline forms. Many granites are apt to be traversed by veins, generally rather more acid in composition than the main body of the rock, and sometimes due to a segregation of the surrounding minerals in rents of the original pasty magma, sometimes to a protrusion of a less coarsely crystalline (aplite, microgranite) material (Fig. 29). Some of the more important of these varieties are distinguished by special names. While in general the quartz and felspar are distributed somewhat evenly in regular grains of fairly uniform size through a large mass of rock, they have sometimes, especially in veins outside a large intrusive mass

[1] On Augite-granite of Old Red Sandstone age in the Cheviot Hills, see J. J. H. Teall, *Geol. Mag.* 1885, p. 106.

[2] *B. S. G. F.* iii. (3rd ser.), p. 210.

crystallised in such a way as to enclose each other and to assume a tendency to an orientation of their longer axes in one general direction, especially when they form the structure known as Pegmatite.[1] One of the most interesting varieties of this structure is that termed Graphic Granite, in which the orientation of the quartz and felspar is singularly well-developed (Fig. 30). The quartz has assumed the shape of long

Fig. 30.—Graphic Granite (nat. size).

imperfect columnar shells, placed parallel to each other and enclosed within the orthoclase, so that a transverse section bears some resemblance to Hebrew writing. The two minerals have crystallised together, with their principal axes parallel. This intergrowth seems to show that there could have been little or no internal movement of the veins, in which it so frequently occurs, when the component minerals assumed their crystalline forms. Where the intergrowth is on a minute scale, and is often in clustered aggregates of radiating and irregular forms, it is known as micropegmatite, which forms the base of the rock known as Granophyre (Fig. 4). This micropegmatitic or granophyric structure characterises large masses of acid eruptive rocks which have broken through the Tertiary basalt-plateaux of the west of Scotland, and which in other parts show a normal granitic texture that cannot be distinguished from that of the most ancient granite.[2]

Some granites present a porphyritic structure, where large crystals of felspar are scattered through the general ground-mass. Fine examples of those phenocrysts are to be seen in some of the granites of Cornwall, which are of later date than the Lower Carboniferous formations. Enclosed dark crystalline concretions, composed particularly of the more basic constituents of the rock, occur in some granites. They are usually ovoid in form and porphyritic in structure; in some cases, they are fragments of other rocks, and are then commonly schistose in structure and irregular in form.[3] In rare examples (Sweden, Ireland, &c.) the component minerals of granite have crystallised with a radial concentric arrangement into rounded ball-like aggregates (spheroidal, orbicular granite, Kugel-granit, Klot-granit).[4] In the centre, as well as round the edges of large bosses of granite, the minerals occasionally assume a more or

[1] For an admirable and exhaustive account of Pegmatite veins, and their associated minerals in Southern Norway, see the great Monograph by Professor W. C. Brögger in Groth's *Zeitsch. Krystallographie*, xvii. (1890).

[2] A. G., *Trans. Roy. Soc. Edin.* xxxv. (1888), p. 147; A. Harker, *Q. J. G. S.* lii. (1896), p. 320.

[3] J. A. Phillips, *Q. J. G. S.* xxxvi. (1880), p. 1.

[4] W. C. Brögger and H. Bäckström, *Geol. Fören. Stockholm*, ix. (1887), p. 307; Hatch, *Q. J. G. S.* xliv. (1888), p. 548, and authorities there cited. Bäckström, *Geol. Fören. Stockholm*, xvi. (1894), p. 107; B. Frosterus, *Bull. Com. Géol. Finland*, No. 4, 1896; F. D. Adams, *Bull. Geol. Soc. Amer.* ix. (1898), p. 163.

less perfectly schistose arrangement. When this takes place, the rock is called gneissose or gneiss granite.[1] (See Book IV. Part VII. p. 723 *et seq.*)

The specific gravity of granite varies from 2·593 to 2·731, and the chemical composition of some of its varieties is shown in the following table of analyses:—

| | I. | II. | III. | IV. | V. | VI. | VII. | VIII. |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 70·60 | 72·24 | 74·82 | 73·38 | 71·90 | 73·27 | 66·83 | 71·62 |
| $TiO_2$ | . | .. | ... | ... | 0·35 | 0·10 | 0·54 | 0·08 |
| $Al_2O_3$ | 16·40 | 14·92 | 16·14 | 14·86 | 14·12 | 15·51 | 15 24 | 14·99 |
| $Fe_2O_3$ | 1·52 | 1·63 | ... | 0·10 | 1·20 | 0·33 | 2·73 | 1·27 |
| FeO | 0·36 | 0·23 | 1·52 | 1·64 | 0·86 | 1·14 | 1·66 | 1·01 |
| MnO | 0·48 | 0·32 | ... | ... | 0·05 | trace | 0·10 | 0·17 |
| MgO | 1·00 | 0·36 | 0·47 | 0·23 | 0 33 | 0·15 | 1·63 | 0·74 |
| CaO | 2·47 | 1·68 | 1·68 | 0·89 | 1·13 | 2·74 | 3·59 | 1·33 |
| $Na_2O$ | 4·14 | 3·51 | 6·12 | 3·94 | 4·52 | 4·79 | 3·10 | 3·62 |
| $K_2O$ | 4·29 | 5·10 | 3·55 | 3·89 | 4·81 | 1·66 | 4·46 | 4·81 |
| Water | ... | ... | ... | 0·82 | 0·60 | 0·68 | 0·56 | 0·41 |
| $P_2O_5$ | ... | .. | ... | .. | 0·11 | trace | 0·18 | trace |
| $ZrO_2$ | ... | ... | ... | ... | 0·04 | ... | 0·04 | ... |
| SrO | ... | ... | ... | ... | ... | ... | 0·03 | ... |
| BaO | ... | ... | .. | ... | 0·04 | ... | 0·11 | ... |
| $Li_2O$ | ... | ... | ... | ... | .. | .. | trace | ... |
| $CO_2$ | ... | ... | ... | ... | 0·21 | ... | trace | ... |
| F | ... | ... | ... | ... | 0·06 | ... | ... | ... |
| Cl | ... | ... | ... | ... | 0·02 | .. | 0·02 | trace |
| $FeS_2$ | ... | ... | ... | ... | trace | ... | .. | ... |
| | 101·26 | 99·99 | 104·30 | 100·25 | 100·35 | 100·37 | 100·82 | 100·05 |

I. From Strontian, Argyllshire, Scotland: coarse-grained with abundant quartz and pink orthoclase, white plagioclase, a little black mica and some titanite. Analysed by Haughton, *Trans. Roy. Irish Acad.* 1866, p. 31.

II. From Doocharry Bridge, Co. Donegal, Ireland: pink orthoclase, grey plagioclase and a little black mica. Analysed by Haughton, *Q. J. G. S.* xviii. (1863), p. 402.

III. From Baveno: the well-known granite with pink orthoclase, white plagioclase, greyish-white quartz and blackish-green mica. Analysed by Bunsen, Roth's 'Gesteinsanalysen,' 1862, p. 66.

IV. From Björketop, Stockholm: grey, fine-grained. Analysed by Hasselbom, *Sverig. Geol. Undersökn*, Section Linde, 1873, p. 16.

V. From Mount Ascutney, Vermont, U.S.A: typical granitite; contains quartz, orthoclase, plagioclase (micro-perthite), biotite, magnetite, sphene, apatite and zircon. Analysed by W. F. Hillebrand, *Bull. U. S. G. S.* No. 168 (1900), p. 24.

VI. From Moore's Quarry, Florence, Massachusetts: biotite-granite, very felspathic; quartz rare, with fluid inclusions; felspar mostly triclinic; orthoclase and microcline present in small quantities, little muscovite, some rutile. Analysed by Eakins, *Bull. U. S. G. S.* No. 168 (1900), p. 30.

VII. From Yosemite Valley, California: hornblende-biotite-granite; contains alkali-felspar, plagioclase, quartz, amphibole, biotite, magnetite and apatite. Analysed by W. Valentine, *Bull. U. S. G. S.*, No. 168 (1900), p. 208.

VIII. From Hurricane Ridge, Crandall Basin, Absaroka Range: aplite dyke; contains quartz, orthoclase, oligoclase, biotite, magnetite, some chlorite and a little hornblende. Analysed by Eakins, *Bull. U. S. G. S.* No. 168 (1900), p. 94.

Surrounding large masses of granite there are usually numerous veins, which consist of granite, quartz-porphyry, felsite, or other member of the granite family. These veins

[1] On foliated granite, see a paper by J. Horne and E. Greenly, *Q. J. G. S.* lii. (1896), p. 633.

are usually much finer in grain than the main body of the rock from which they diverge. Lossen has shown that the Bode vein in the Harz has a granitoid centre, with compact porphyry sides, in which he found with the microscope a true glassy base.[1] From the margin of the Tertiary granite and granophyre of Skye proceed broad dykes, which show the most perfect flow-structure and are crowded with spherulites.[2] Sometimes the rocks associated in this way with granite differ in composition from the main granite, and this is more especially apt to occur where the peripheral part of the granite has assumed a more basic character than the rest of the mass. Tourmaline is one of the characteristic minerals of granite-veins, though less observable in the main body of the rock; with quartz, it forms Schorl-rock.

Granite weathers chiefly by the decay of its felspars. These are converted into kaolin, the mica becomes yellow and soft, while the quartz stands out scarcely affected. The granite of the south-west of England has weathered to a depth of 50 feet and upwards, so that it can be dug out with a spade, and is largely used as a source of porcelain-clay.

Granite occurs (1) as an eruptive rock, forming huge bosses, which rise through other formations both stratified and unstratified, and sending out veins into the surrounding and overlying rocks, which usually show evidence of much alteration as they approach the granite; (2) connected with true volcanic rocks and forming, perhaps, the lower portions of masses which flowed out at the surface as lavas. In the Tertiary volcanic region of the west of Scotland masses of granite and granophyre have pierced the sheets of subaerial basalts and must have risen near to, if they did not actually reach the surface. They prove that granite is not necessarily, though usually, an abysmal rock.

**Granite-porphyry** (Micro-granite),[3] a fine-grained granitoid rock having a holocrystalline, occasionally granophyric (micropegmatitic) matrix, composed mainly of alkali-felspar and quartz, through which are dispersed large crystals of orthoclase and plagioclase, with smaller blebs and imperfect crystals of quartz, hexagonal plates of biotite and occasionally some hornblende or pyroxene. It occurs as part of large bosses which consist mainly of granite, but is probably most frequently found in veins which no doubt are connected with some body of granite.

The variations in composition and structure of the rocks connected with large eruptive bosses or stocks has been well worked out in Southern Norway, where Professor Brögger has made known the chemical constitution of a number of dykes and veins which he believes to represent different stages in the differentiation of one original magma. The most acid variety found by him is the following:—

Grorudite—a compact greenish fine-grained aggregate of alkali-felspar and albite (often as microperthite), or less frequently soda-orthoclase (also sometimes anorthoclase), aegerine, and a greater or less abundance of quartz. Some of these minerals occur also in large dispersed crystals, together with hornblende and mica. This rock is found in numerous veins in the Christiania district, which were at first grouped as examples of aegerine-granite-porphyry. It is regarded by Brögger as the acid end of a group which he names the Grorudite-Tinguaite series. An average sample has the following chemical composition, $SiO_2$ 74·35; $Al_2O_3$ 8·73; $Fe_2O_3$ 5·84; FeO 1·00; MnO 0·22; MgO 0·07; CaO 0·45; $Na_2O$ 4·51; $K_2O$ 3·96: loss 0·25: total 99·38. But great differences were noted between the chemical constitution of the centre and margins of some of the dykes. Thus in the centre of a dyke at Grorud the percentage of silica was 70·15, while that of the margin was only 66·50. In the next member of the series, called Sölvsbergite, the silica amounts to 64·92 and in Tinguaite to no more than 56·58. These rocks are further noticed at p. 221.

[1] *Z. D. G. G.* xxvi. (1874), p. 856. [2] A. G., *Q. J. G. S.* l. (1894), p. 221.

[3] J. P. Iddings, *Monograph* xx. *U. S. G. S.* Appendix B, p. 339. The term "Porphyry" has been restricted by some petrographers to rocks in which the alkali-felspars are predominant (see Porphyrite, p. 219).

**Quartz-porphyry** (Eurite, Microgranite, Elvan).[1] This term has been variously applied. In its widest use it has been made to include rocks which have a minutely holocrystalline (microgranitic) texture, and are thus only fine-grained varieties of granite-porphyry; also rocks that possess a base which is not definitely individualised, but sometimes includes distinctly devitrified glass, and is thus linked with the Rhyolites. The term is here employed to embrace rocks distinguished by an exceedingly close-grained, grey, pink or brown ground-mass, which under the microscope may be resolved into a microgranitic aggregate of quartz and felspar, not infrequently grouped in a micro-pegmatitic arrangement (granophyre), or which, if not so resolvable, by having a cryptocrystalline or micro-felsitic texture show a high percentage of silica on being chemically tested. Through their ground-mass are scattered phenocrysts of quartz, sometimes in doubly-terminated pyramids, and orthoclase, sometimes with plagioclase, biotite and hornblende.

That some at least of the quartz-porphyries were once probably vitreous rocks and have attained their present condition through processes of devitrification, has long been held by some able petrographers. As far back as 1867 Vogelsang thought that the Halle porphyry and other porphyries which he had seen were probably once vitreous masses.[2] And Lossen,[3] whose observations on the Bode vein have already been cited, was led to the belief that the ground-mass of the Hartz porphyries had once been a glass like obsidian. Some of the so-called "pitchstones" appear to be glassy forms of quartz-porphyry. Thus no sharp line can be drawn between rocks of a holocrystalline and granitic character and those which are mere glass. Intermediate varieties may be found representing the successive stages from the one condition into the other.[4]

The average specific gravity of the quartz-porphyries may be taken to be about 2·65, and their chemical composition may be inferred from the following analyses of a few illustrative examples :—

| | I. | II. | III. | IV. |
|---|---|---|---|---|
| $SiO_2$ | 74·44 | 71·46 | 73·12 | 72·79 |
| $Al_2O_3$ | 13·51 | 15·38 | 14·27 | 13·77 |
| $Fe_2O_3$ | ... | 0·30 | 0·51 | 3·32 |
| $FeO$ | 2·25 | 2·27 | 0·26 | ... |
| $MgO$ | 0·01 | 0·22 | 0·24 | 0·62 |
| $CaO$ | 1·19 | 0·47 | 1·10 | 1·94 |
| $Na_2O$ | 1·40 | 2·79 | 3·43 | 4·12 |
| $K_2O$ | 5·31 | 5·51 | 4·90 | 2·99 |
| $H_2O$ | 1·34 | 1·70 | 1·41 | 1·08 |
| $TiO_2$ | ... | ... | 0·08 | ... |
| $P_2O_5$ | ... | ... | 0·03 | ... |
| $MnO$ | ... | trace | 0·06 | trace |
| $SrO$ | ... | ... | trace | ... |
| $BaO$ | ... | ... | trace | ... |
| $Li_2O$ | ... | ... | trace | ... |
| $CO_2$ | ... | ... | 0·77 | ... |
| | 99·45 | 100·10 | 100·18 | 100·63 |

[1] "Elvan" is a Cornish name for a variety of quartz-porphyry, which forms veins that proceed from masses of granite into the surrounding slates or "Killas," or are only found near the granite. It consists of a crystalline-granular aggregate of quartz and orthoclase. J. A. Phillips, *Q. J. G. S.* xxxi. p. 334.

[2] 'Philosophie der Geologie,' p. 194.

[3] *Abhandl. Acad. Berlin*, 1869, p. 85.

[4] Mr. Pirsson discards the term "quartz-porphyry" as logically objectionable and adopts in its place "rhyolite-porphyry," 20th *Ann. Rep. U. S. G. S.* Part iii. p. 520. He looks on granite, granite-porphyry, quartz-porphyry and rhyolite as marking phases in one great continuous series of rocks. *Bull. U. S. G. S.* No. 189, p. 81.

I. Ground-mass of the quartz-porphyry of the lower Holzemmenthal in the Hartz. Analysed by Streng, *Neues Jahrb.* 1860, p. 152.

II. Fine-grained "Elvan," Mellanear, Cornwall. Analysed by J. A. Phillips, *Q. J. G. S.* xxxi. (1875), p. 335.

III. Quartz-porphyry, Yogo Peak, Montana: phenocrysts of orthoclase and quartz in a ground-mass of quartz and alkali-felspar, with a little white mica and some kaolin; chlorite, limonite and calcite are also present, pseudomorphous after biotite, and perhaps hornblende; total amount of secondary minerals very small. Analysed by W. F. Hillebrand, *B. U. S. G. S.* No. 168 (1900), p. 125.

IV. From the volcanic series of Llyn-y-Gader, Cader Idris, Wales. Analysed by Mr. Holland, *Q. J. G. S.* xlv. (1889), p. 435. The large proportion of soda in this rock connects it with the siliceous keratophyres (p. 219).

The colour of the quartz-porphyries depends chiefly upon that of the felspar,—pale flesh-red, reddish-brown, purple, yellow, bluish or slate-grey, passing into white, being in different places characteristic. It will be observed in this, as in other rocks containing much felspar, that the colour, besides depending on the hue of that mineral, is greatly regulated by the nature and stage of decomposition. A rock, weathering externally with a pale yellow or white crust, may be found to be dark in the central undecayed portion. When the base is very compact, and the felspar-crystals well defined and of a different colour from the base, the rock, as it takes a good polish, may be used with effect as an ornamental stone. In popular language, such a stone is classed with the "marbles," under the name of "porphyry."

The quartz-porphyries occur with plutonic rocks, as eruptive bosses or veins, often associated with granite, from which, indeed, they may be seen to proceed directly; of frequent occurrence also by themselves as veins and irregularly intruded masses among highly convoluted rocks, especially where these have been more or less metamorphosed.

### ii. Rhyolite Family.

This family is essentially of volcanic origin. Petrographers who are still under the spell of the Wernerian belief that rocks can be classified on a chronological basis, place the rhyolites among the Tertiary and modern products of volcanic action. It is undoubtedly true that the freshest and most typical rhyolites belong to the later geological periods, but rocks that cannot be distinguished from them by any really essential characters occur even among the older Palæozoic formations. Such ancient rocks are assigned by these writers to the group of the quartz-porphyries. By other observers, however, they are classed with their modern representatives as one great family. The more modern and typical forms will here be described first.

**Rhyolite (Liparite)**—under this name the most acid lavas are grouped, their percentage of silica rising even to 77. They are distinguished by a greater variability in structure and texture than any other igneous rocks, ranging from the most perfect glass to a holocrystalline aggregate, which might even be mistaken for granite, many of these different structures actually alternating with each other in the same sheet of rock. Rhyolite is the name applied more particularly to the lithoid varieties, while the glassy form is known as Obsidian, but the two types of structure may be found alternating in the same lava-flow.

Under the name of Nevadite Baron von Richthofen described a form of Rhyolite abundantly developed in Nevada and characterised by its resemblance to granite, owing to the abundance of its porphyritic crystals, and the relatively small amount of ground-mass in which they are imbedded. The granitoid aspect is external only, as the ground-mass is distinct, and varies from a holocrystalline character to one with abundant glass, and the texture ranges from dense to porous.[1] The presence of such a ground-mass

[1] Richthofen, *Z. D. G. G.* xx. (1868), p. 680. See also Hague and Iddings, *Amer.*

is characteristic throughout the rhyolites. It is for the most part a compact pale-grey, yellowish, greenish, reddish or black substance, which may here and there be pure glass with few or no microlites, but it rapidly becomes lithoid by the development in it of microlitic, spherulitic, microcrystalline, perlitic or pumiceous structures. Under the microscope, when not simply vitreous, it presents an enamel-like, porcellanous aspect, more or less crowded with microlites, and often with minute spherulites and perlitic cracks. It is constantly marked by traces of flow, in alternating, lenticular streaks of darker and lighter substance, the microlites and spherulites being arranged along these streaks and curving round the large included phenocrysts. The dispersed crystals consist of quartz, sanidine, plagioclase, biotite, augite and magnetite. The quartz crystals are distinguished from those of the granite family by the absence of liquid cavities and by the presence of inclusions of glass and gas, some of the cavities having a dihexahedral form (negative crystals).

It has been inferred by Mr. Iddings that the phenocrysts must have been of late and comparatively rapid growth in the outflowing magma, because they are so promiscuously distributed through the rock and contain such an abundance of inclusions of the mother-liquor and gas-cavities. It is difficult to suppose that in a magma having a specific gravity of only 2·3 fairly large crystals of augite (sp. gr. 3·3) and magnetite sp. gr. 5·0) could remain long suspended without finding their way by gravitation to the bottom.[1] On the other hand, the curiously corroded margins of the crystals in some sanidines seem to point to the solvent action of the magma upon them.

The microscopic crystals in the base of rhyolite show a marked tendency to form intergrowths and also compound groups of crystals. Thus the micrographic intergrowth of quartz and sanidine has been described as of frequent occurrence in the obsidians of the Yellowstone Park,[2] from aggregates visible to the naked eye down to microscopic proportions, and the gradual stages of accretion can be traced wherein the first crystallisations of felspar and quartz from the molten magma gradually build up oval and spherical bodies, which become spherulites wherein the individuality of the original crystalline fibres is lost. By the continued growth of such aggregates, the glass has become lithoid. Besides the spherules, which vary in size from nut-like or pea-like forms down to granules only discernible with the microscope, much larger nodular bodies make their appearance in some vitreous rhyolites, to which the name of *Lithophyses* has been given. These range up to a foot in diameter, and are mostly hemispherical in form. They each consist of a series of delicate concentric shells, which arch over one another like the petals of a rose, and are so thin that sometimes fifty of them may be counted within a radius of two inches, and so fragile as to crumble under the touch, being made up of small and slightly adhering crystals of quartz and orthoclase. The origin of these bodies is believed to be traceable to the more abundant presence of highly heated water-vapour in spots in the magma, the greater viscosity of the surrounding magma, and the very rapid crystallisation of jointed rods of felspar followed by further condensation upon the crystallisation of the silica. These changes and their results are like those produced artificially in closed tubes, where the action of highly heated water-vapour

*Journ. Sci.* xxvii. (1884), p. 461. These authors distinguish between Nevadite and Liparite, the latter being characterised by the small number of porphyritic crystals imbedded in a relatively large amount of ground-mass which, as in Nevadite, may be holocrystalline or glassy. They also distinguish *Lithoidal Rhyolite* and *Hyaline Rhyolite* as additional varieties. Messrs. L. Duparc and E. Pearce have recently described a variety of the rock under the name of *Plagioliparite*, its distinguishing feature being the presence of phenocrysts of biotite, plagioclases and quartz, with an entire absence of orthoclase. *Compt. rend.* Jan. 1900.

[1] *Monograph* xxxii. (1899) *U. S. Geol. Surv.* Part ii. p. 267; The spherulitic and lithophyse structures of rhyolites are fully discussed in this important memoir by Messrs. J. P. Iddings and W. H. Weed.

[2] Iddings, *7th Ann. Rep. U. S. G. S.* (1888), p. 274, and *Monogr.* xxxii. p. 410.

has been tested by experiment.[1] The lithophyses of some rhyolites in Colorado contain crystals of topaz and spessartite garnet.[2]

The remarkable variability of the rhyolites in regard to texture may be seen even in a single sheet of lava. In some regions (Lipari) the surface of the outflow remains tolerably solid, but in others (Yellowstone Park) it has been converted into pumice by the expansion of its contained water-vapour. Below this pumiceous crust the rock passes into solid glass, the central portion of the sheet becoming lithoidal by the development of a microspherulitic or other structure, while the lower parts are glassy, passing down even into pumice, which at the bottom has sometimes broken up into a kind of breccia or tuff by the weight and movement of the overlying mass. Some rhyolites are full of small and large cavities, which are lined with chalcedony, quartz, amethyst, jasper or other minerals. Columnar structure is well displayed in certain volcanic districts, some of the rhyolites in the Yellowstone Park displaying columns 200 feet in height.

The cause of the wide range of variability in the texture of rhyolitic lavas, as compared with those of the basic families, is probably to be sought in the greater viscosity and heterogeneous character of the acid magma. Portions of the lava still retaining their original condition of nearly pure glass are spread out into thin lenticular layers as the mass moves onward; those parts that have become lithoidal by the development of spherulites or of the pumiceous structure are likewise flattened into thin leaves and laminæ, so that the whole mass comes to be built up of rapidly alternating lenticular layers of material (eutaxitic structure), having throughout the same chemical composition, but varying considerably in texture, mainly according to the distribution of water-vapour through the lava and the attendant devitrification.

The specific gravity of rhyolite ranges from about 2·39 to 2·75, with an average of about 2·5. The chemical constitution of a number of modern and ancient members of the family is shown in the accompanying table of analyses:—

| | I. | II. | III. | IV. | V. | VI. | VII. | VIII. |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 74·24 | 75·89 | 74·70 | 75·52 | 83·802 | 74·88 | 72·6 | 72·18 |
| $Al_2O_3$ | 14·50 | 12·27 | 13·72 | 14·11 | 7·686 | 12·00 | 12·4 | 14·46 |
| $Fe_2O_3$ | 1·27 | 1·12 | 1·01 | 1·74 | 0·111 | 3·50 | 0·7 | 1·78 |
| $FeO$ | 0·67 | 1·37 | 0·62 | 0·08 | 0·408 | 0·20 | 1·1 | 0·91 |
| $MgO$ | 0·25 | 0·29 | 0·14 | 0·10 | 0·109 | 1·28 | trace | trace |
| $CaO$ | 0·11 | 0·86 | 0·78 | 0·78 | 0·896 | 0·34 | 0·9 | 0·92 |
| $Na_2O$ | 3·00 | 3·23 | 3·90 | 3·92 | 4·229 | 2·49 | 1·7 | 1·92 |
| $K_2O$ | 3·66 | 3·42 | 4·02 | 3·63 | 2·161 | 4·77 | 4·7 | 6·10 |
| $H_2O$ | 2·04 | 0·82 | 0·62 | 0·39 | ... | ... | 5·2 | 1·47 |
| $TiO_2$ | 0·20 | 0·50 | none | none | ... | ... | ... | ... |
| $P_2O_5$ | 0·07 | none | none | ... | 0·089 | ... | ... | ... |
| $MnO$ | 0·06 | none | trace | none | ... | ... | ... | trace |
| $Li_2O$ | none | 0·01 | ... | ... | ... | ... | ... | ... |
| $SO_3$ | 0·03 | 0·28 | ... | ... | 0·017 | ... | ... | ... |
| $SrO$ | trace | ... | ... | ... | ... | ... | ... | ... |
| $BaO$ | 0·18 | ... | ... | ... | ... | ... | ... | ... |
| $FeS_2$ | ... | ... | 0·40 | 0·11 | 0·191 | ... | ... | ... |
| Loss | ... | ... | ... | ... | 0·301 | 1·20 | ... | ... |
| | 100·28 | 100·06 | 99·91 | 100·38 | 99·894 | 100·66 | 99·3 | 99·74 |

I. Rhyolite, Lassen Peak region, California. Analysed by W. F. Hillebrand, *U. S. G. S.* No. 168 (1900), p. 178. A light-grey rock, with occasional phenocrysts of quartz and felspar in a granular ground-mass of the same materials.

II. Rhyolite, Mount Sheridan, Yellowstone region. Analysed by J. E. Whitfield,

[1] Iddings, *Monogr.* xxxii. p. 418, and authorities there cited.

[2] Whitman Cross, *Amer. Journ. Sci.* xxi. (1886), p. 432.

*op. cit.* p. 105. Composition reported by Mr. Iddings as quartz and sanidine, with a little magnetite and augite.

III. Black Obsidian, Obsidian Cliff, Yellowstone Park. Analysed by J. E. Whitfield, *op. cit.* p. 104. This rock is described by J. P. Iddings in 7th *Ann. Rep. U. S. G. S.* 1888, p. 249. *Monograph* xxxii. Part ii. p. 359. It contains microlites of augite and magnetite, with traces of quartz and felspars.

IV. Red Obsidian, Obsidian Cliff, Yellowstone Park. Analysed by J. E. Whitfield, *ibid.*, also described by Mr. Iddings in same Report and Monograph; resembles No. III., with ferric oxide replacing magnetite.

V. Felsite (felsophyre) from summit of Aran Mowddy, Wales. Analysed by J. Hughes, *Q. J. G. S.* xxxi. p. 400. Contains porphyritic crystals in a felsitic matrix. Teall, 'British Petrog.' p. 339.

VI. Pale-green Felsite, from near Pitt's Head. Analysed by Haughton, *Trans. Roy. Irish Acad.* xxxiii. p. 615. Teall, *loc. cit.*

VII. Pitchstone from Arran. Analysed by J. H. Player. Teall, *op. cit.* p. 347.

VIII. Devitrified perlitic Pitchstone, Lea Rock quarry, Shropshire. Analysed by Mr. Phillips, *Q. J. G. S.* xxxiii. p. 457. The specific gravity of this rock is 2·62. Teall, *op. cit.* p. 341.

Rhyolite is an extremely acid rock of volcanic origin. It forms enormous masses in the heart of extinct volcanic districts in Europe (Hungary, Euganean Hills, Iceland, Lipari), and in North America (Wyoming, Utah, Idaho, Oregon, California). It occurs both as intrusive dykes, sheets and bosses, and as outflows of lava at the surface. Some of the most magnificent displays of this rock are those of the Yellowstone National Park in the Western United States, where it forms a vast plateau, sends arms into the valleys in the surrounding mountains, lies in denuded remnants on their slopes, and in places exceeds 2000 feet in the thickness of its successive sheets.[1]

Pantellerite—a group of rocks first described by H. Förstner from the Island of Pantelleria, characterised by a structure varying from glassy into finely granular and trachytic varieties, and a chemical composition in which the percentage of silica ranges between 66·8 and 72·5, while the alkalies amount to 10 per cent, soda being largely predominant. The specific gravity is 2·4 in the vitreous and 2·6 in the holocrystalline varieties.[2]

The vitreous members of the Rhyolite family form an interesting group, in which we may detect what was probably the original condition of the molten magma. Every gradation can be traced from a perfect glass into a thoroughly devitrified and even crystalline rock. As already remarked, the original vitreous condition of rhyolite can still be seen even with the naked eye in the clots and streaks of glass that occasionally run through it in the direction of its flow-structure. Various names have been given to the glassy rocks, of which the chief are obsidian, pumice, and pearlstone or perlite. These, however, are not to be regarded as distinct rock-species, but rather as the glassy condition of rhyolitic lavas.

Obsidian (rhyolite-glass)—the most perfect form of volcanic glass, externally resembling bottle glass, having a perfect conchoidal fracture, and breaking into sharp splinters, transparent at the edges. Its colours are black, brown, or greyish-green,

[1] On rhyolite, besides works already cited, the following may be specially referred to: F. von Richthofen, *Jahrb. K. K. Geol. Reichsanst*, xi. (1861), p. 156. Zirkel, 'Micro. Petrog.' p. 168. King, 'Explor. 40th Parallel,' i. p. 606; Whitman Cross, *Monograph* xii. *U. S. G. S.* (1886), p. 345; W. H. Weed and L. V. Pirsson, *B. U. S. G. S.* No. 139 (1896), p. 118. 20*th Ann. Rep. U. S. G. S.* (1900), pp. 177, 351, 520; E. Ordoñez, "Las Rhyolitas de Mexico," *Bol. Inst. Geol. Mexico*, No. 14 (1900), No. 15 (1901); Thoroddsen, *Geol. Fören. Stockholm*, xiii. (1891), p. 609; H. Bäckström, *op. cit.* pp. 687-682; N. O. Holst. *Sver. Geol. Undersökn*, No. 110 (1890); J. Park and F. Rutley, *Q. J. G. S.* lv. (1899), p. 449.

[2] *Bull. Com. Geol. Ital.* 1881.

rarely yellow, blue, or red, but not infrequently streaked or banded with paler and darker hues. A thin slice of obsidian prepared for the microscope is found to be very pale yellow, brown, grey, or nearly colourless, and on being magnified shows that the usual dark colours are almost always produced by the presence of minute opaque microlites, which present themselves sometimes as black opaque trichites, beautifully arranged in eddy-like lines showing the original fluid movement of the rock (Fig. 18); also as rod-like transparent forms. They occasionally so increase in abundance as to make the rock lose the aspect of a glass and assume that of a dull flint-like or enamel-like stone. This devitrification can only be properly studied with the microscope. It is rare to find the glass of obsidian perfectly free from crystallites. They are fewest in the highly pumiceous parts of the rock, as if the sudden expansion of the vapours enclosed in the magma had led to the chilling of the molten material, thus preventing the microlitic minerals from crystallising before the solidification of the glass.[1] Dull grey enamel-like spherulites appear in some parts of the rock in great abundance, drawn out into layers, so as to give the rock a fissile structure, while steam- or gas-cavities likewise occur, sometimes so large and abundant as to impart a cellular aspect. The lithophyses above referred to are conspicuous in some of the Yellowstone obsidians.[2] The occurrence of abundant sanidine crystals gives rise to *Porphyritic Obsidian*. Many obsidians, from the increase in the number of their steam-vesicles, pass into pumice. Now and then, the steam-pores are found in enormous numbers, of extremely minute size, as in an obsidian from Iceland, a plane of which, about one square millimetre in size, has been estimated to include 800,000 pores. The chemical composition of obsidian may be judged from the analysis of two characteristic examples given in the table on p. 212. The specific gravity of the glassy rocks being normally less than that of the crystalline forms, obsidian is less heavy than rhyolite; its specific gravity averages between 2·35 and 2·45. This rock occurs as a product of the volcanoes of late geological periods. It is found in Lipari, Iceland, and Teneriffe; in North America, it has been erupted from many points among the Western United States; it is met with also in New Zealand.[3]

Pumice (Ponce, Bimstein)—a general term for the loose, spongy, cellular, filamentous or froth-like parts of lavas, but when the word is used by itself it is generally understood to refer to the Rhyolite family. So distinctive is this structure, that the term *pumiceous* has come into common use to describe it. There can be no doubt that this froth-like rock owes its peculiarity to the abundant escape of steam or gas through its mass while still in a state of fusion. The most perfect forms of pumice are found among the acid lavas, but the same type of structure may be met with in the lavas of the intermediate and basic series. Microscopic examination of a rhyolitic pumice reveals a glass crowded with enormous numbers of minute gas- or vapour-cavities, usually drawn out in one direction, also abundant crystallites like those of obsidian. Owing to its porous nature, pumice possesses great buoyancy and readily floats on water, drifting on the ocean to distances of many hundreds of miles from land, until the cells are gradually filled with water, when the floating masses sink to the bottom.[4] Abundant rounded blocks of pumice were dredged up by the *Challenger* from the floor of the Atlantic and Pacific Oceans.

Perlite (Pearlstone) was the name given to what was at first supposed to be a distinct rock species, but which is now recognised to be only a phase in the devitrification of an acid volcanic glass. As the word indicates, the structure of the rock presents enamel-like or vitreous globules which, occasionally assuming polygonal forms by mutual pressure, sometimes constitute the entire rock, their outer portions shading off

[1] *Monogr. U. S. G. S.* xxxii. Part ii. p. 403.

[2] *Monogr. U. S. G. S.* No. xxxii. Part ii. chap. x.

[3] Most of the memoirs on rhyolite above cited treat also of obsidian.

[4] On porosity hydration, and flotation of pumice, see Bischof, 'Chem. und Phys. Geol.' suppl. (1871), p. 177.

into each other, so as to form a compact mass; in other cases, separated by and cemented in a compact glass or enamel. They consist of successive very thin shells, which, in a transverse section, are seen as coiled or spiral rings, usually full of the same kind of hair-like crystallites and crystals as in the more glassy parts of the rhyolite (Fig. 8). As these bodies both singly and in fluxion-streams traverse the globules, the latter may be regarded as a structure developed by contraction in the rock, during its consolidation, analogous to the concentric spheroidal structure seen in weathered basalt (Fig. 94). Among these concentrically laminated globules true spherulites occur, distinguished by their internal radiating fibrous structure (Figs. 6, 16).

Regarding the origin of the members of the rhyolite family described above, there can be no great diversity of opinion, for they are so fresh and present their structures so clearly that their history can readily be followed through its successive stages. In the rocks of which an account has now to be given the history is not always so manifest. They are of all ages, going back to older Palæozoic and even pre-Cambrian times. They include a series of varieties which range from thoroughly lithoid and even crystalline structures to a completely vitreous condition. The German school of petrographers, making use of relative antiquity as a basis of separation, has grouped these rocks with the quartz-porphyries and pitchstones, regarding them as quite distinct from the rhyolites. The British School, on the other hand, finding essentially the same structures in them as in the rhyolites, has been unable to make any separation between the two groups of rock, and places them all in the Rhyolitic family. Formerly the lithoid varieties were classed under the general name of "felsites" ("felstones"), but this term has been so differently employed that a careful definition is required of the sense in which it is used. By many writers it is now applied rather to a fine-grained lithoid texture than to a special species or variety of rock. The history of this word and the difficulties which have attended the study of the rocks to which it was applied are well stated by Miss Bascom, who has investigated an important series of ancient volcanic rocks in the South Mountain, Pennsylvania, in the course of which she came to realise the unsatisfactory character of the nomenclature, and to propose an amendment of it.[1] She has proposed to place with the quartz-porphyries all the acid volcanic rocks which were originally holocrystalline or whose original character is in doubt, and to group under the term *Aporhyolite* all those which by their structure can be shown to have been once glassy. This new term would include most of the felsites of the British School and much of what is called "felsitfels" on the Continent.

Under the name of **Felsite** (Felstone), **Felsitfels** or **Aporhyolite**, a large series of rocks may be grouped which appear for the most part to have been originally vitreous lavas like the rhyolites, but which have undergone complete devitrification, though frequently retaining the perlitic, spherulitic and flow-structures. They vary in colour from nearly white through shades of grey, blue and red or brown to nearly black, often weathering with a white crust. They are close-grained in texture, often breaking with a subconchoidal fracture and showing translucent edges. Porphyritic felspars (both orthoclase and plagioclase) and blebs of quartz are of frequent occurrence. The flow-structure is occasionally strongly marked by bands (taxites) of different colour, texture and partly also of composition, sometimes curiously bent and curled over, indicating the direction of movement of the still unconsolidated rock. The spherulitic structure also may be found so strongly marked that the individual spherules measure an inch or more in diameter, so that the rock seems composed of an aggregate of balls, and was formerly mistaken for a conglomerate (*Pyromeride, nodular felsite*).[2] Under the micro-

[1] *Journ. Geol.* i. (1893), p. 829; *Bull. U. S. G. S.* No. 136 (1890), chap. iv.; J. Morgan Clements, *Journ. Geol.* iii. (1895), p. 817.

[2] On nodular felsites see Professor Bonney, *Q. J. G. S.* xxxviii. (1882), p. 289; G. Cole, *Q. J. G. S.* xli. (1885), p. 162; xlii. p. 183; Miss Raisin, *op. cit.* xlv. (1889), p. 247. Harker, "Bala Volcanic Rocks," 1889, p. 28.

scope many of the typical structures of rhyolite can be detected in these rocks. One of the earliest observers who recognised these features was the late Mr. Allport, who described some ancient examples of perlitic structure from Shropshire in what were probably once ordinary rhyolites,[1] and Mr. Rutley afterwards detected the presence of the same structure in the Lower Silurian lavas (felstones) of North Wales.[2]

The ground-mass of these rocks, as already remarked, has given rise to much discussion, but it is now generally recognised as an altered condition of the devitrification of an original vitreous mass (p. 149). Secondary changes have in large measure destroyed the original microlitic structure, but traces of it can often be found, while the spherulitic and perlitic forms frequently remain almost as fresh as in a recent rock. Rocks having these characters have been found abundantly as interbedded lavas with accompanying tuffs and agglomerates among the Silurian and older rocks in Wales and Shropshire, in the Lake District, and in other parts of the British Isles. They have been met with on the Continent of Europe even of pre-Cambrian age, as in Finland. Extensive areas of them occur also in different parts of the United States.

Under the name of Felsite porphyry Professor Tschermak has grouped a series of rocks having a compact ground-mass of quartz and alkali-felspar, with scattered porphyritic crystals of orthoclase but not of quartz, and having the chemical composition of quartz-porphyry. The name has likewise been employed in the same sense in the United States, and applied to dyke-rocks showing sometimes flow-structure and apparently resulting from the devitrification of an original glassy magma. Gradations from such rocks into syenite porphyry have also been noted.[3]

Pitchstone, like Felsite, is a term now more usually employed to denote a peculiar condition of the less perfectly glassy acid rocks than any one special rock-species. The rocks so designated possess a resinous or pitch-like lustre, and show internally a more advanced development of microlites than in obsidian. They thus represent a further stage of devitrification. These rocks are easily frangible, breaking with a somewhat splintery fracture, translucent on thin edges, with usually a black or dark green colour, that ranges through shades of green, brown, and yellow to nearly white. Examined microscopically, they are found to consist of glass in which are diffused hair-like feathery and rod-shaped microlites, or more definitely formed crystals of orthoclase, plagioclase, quartz, hornblende, augite, magnetite, &c. The pitchstone of Corriegills, in the island of Arran, presents abundant green, feathery, and dendritic microlites of hornblende (Fig. 13).[4] Occasionally, as in Arran, pitchstone assumes a spherulitic or perlitic structure. Sometimes it becomes porphyritic, by the development of abundant sanidine crystals. Rocks possessing pitchstone characters are found as intrusive dykes, veins, or bosses, probably in close connection with former volcanic activity, as in the case of the dykes, which in Arran traverse Lower Carboniferous rocks, but are probably of Miocene age, and those which in Meissen send veins through and overspread the younger Palæozoic felsite-porphyries.

### iii. Syenite Family.

**Syenite.**—This name, formerly given in England to a granite with hornblende replacing mica, is now restricted to a rock consisting essentially of a holocrystalline mixture of orthoclase and hornblende, to which plagioclase, biotite, augite, magnetite, or quartz may be added. As already mentioned, the word, first used by Pliny in reference to the rock of Syene, was introduced by Werner as a scientific designation. It was applied by him to the rock of the Plauenscher-Grund, Dresden; he afterwards, however, made that rock a greenstone. The base of all syenites, like that of granites,

[1] *Q. J. G. S.* xxxiii. p. 449. [2] *Op. cit.* xxxv. p. 508.

[3] Tschermak, *Sitzb. Acad.* Vienna, lvi. (1867), p. 305. L. V. Pirsson, *Bull. U. S. G. S.* No. 139 (1896), p. 103.

[4] See F. A. Gooch, *Min. Mittheil.* 1876, p. 185. Allport, *Geol. Mag.* 1881, p. 438.

is thoroughly crystalline, without an amorphous ground-mass. The typical syenite of the Plauenscher-Grund, formerly described as a coarse-grained mixture of flesh-coloured orthoclase and black hornblende, containing no quartz, and with no indication of plagioclase, was regarded as a normal orthoclase-hornblende rock. Microscopical research has, however, shown that well-striated triclinic felspars, as well as quartz, occur in it. Rocks which may be classed together under the general designation of syenite may be subdivided into three groups: 1st, Syenite proper or Hornblende syenite, consisting of alkali-felspar and hornblende; 2nd, Mica-syenite, a mixture of alkali-felspar and biotite, and 3rd, Augite-syenite, made up of alkali-felspar and augite or diallage. Some varieties of syenite have been distinguished by special names. Monzonite, named after Monzoni in the S.E. Tyrol, is there an augite-syenite consisting of a crystalline aggregate of orthoclase, plagioclase, and augite with a little accessory biotite. The term, however, has been greatly widened in its use by Professor Brögger, who includes in it a large group of rocks intermediate between granites and syenites on the one hand, and diorites and gabbros on the other, with a silica percentage ranging from 73 per cent at the one end (acid quartz-monzonite, Adamellite) to 46 per cent at the other (olivine-monzonite). Other types have been distinguished in Southern Norway, chiefly by Brögger's minute researches. Among these is Laurvikite, an aggregate of soda-orthoclase or soda-microcline (seldom also plagioclase) with a little pyroxene, hornblende, olivine, magnetite and apatite. A more acid variety in the same region has been named Akerite (quartz-syenite) and contains in addition to the alkali-felspar, plagioclase, greenish pyroxene, biotite and a little quartz. Nordmarkite is another acid quartziferous type containing, besides its orthoclase (or microperthite and acid oligoclase) and quartz, biotite, hornblende, pyroxene, always sphene, some aegerine and zircon, iron-ore and apatite; its silica percentage is from 60 to 64, with about 12 or 13 per cent of alkalies, the soda predominating.[1] Another basic variety recently found among the intrusions connected with granite in Argyllshire and named Kentallenite, consists of olivine and augite with orthoclase and augite in varying proportions and biotite.[2]

Like the granites, the syenites include aplitic (syenite-aplite) and pegmatitic (syenite-pegmatite) varieties. These are well displayed in the Christiania region, where they have been studied in great detail by Brögger. The pegmatite veins are there particularly rich in rare minerals.[3]

**Syenite-porphyry**—a name given to rocks having the mineralogical and chemical constitution of syenites but showing phenocrysts of orthoclase, hornblende, biotite or augite dispersed through a holocrystalline ground-mass without any non-crystalline base. They occur principally in dykes. The analysis of an example of these is given in the accompanying table. Where the syenitic material has been injected into narrow fissures and has solidified as an exceedingly compact rock it has been called *Syenite-aphanite*.

The syenites are less abundant than the granites, but occur in similar relations to the surrounding rocks. They are found as bosses, intrusive sheets and dykes, and, like

[1] See Brögger's monograph, "Die Eruptivgesteine des Kristianiagebietes," Parts i. and ii. (1894-95). This volume contains a full summary of the literature connected with the geology of the Monzoni and Predazzo region. References to subsequent papers will be found in Dr. J. Romberg's "Geologisch-petrographische Studien im Gebiete von Predazzo," *Sitz. Berlin Akad.*, 1902, pp. 675, 781. More than two hundred separate comprehensive memoirs in five different languages have been contributed to the discussion of this classic part of Europe. The latest contribution, by Dr. Romberg, gives only the first instalment of a renewed study of these rocks, based on a larger collection of specimens (2000), a fuller series of microscopic slides (more than 1000), and a more detailed chemical examination.

[2] Messrs. Hill and Kynaston, *Q. J. G. S.* lvi. (1900), p. 531.

[3] Brögger enumerates no fewer than seventy-three minerals from these veins. "Die Mineralien der Syenitpegmatitgänge der Sudnorwegischen Augit und Nepheline-syenite," *Zeitsch. fur. Kryst.* xvi. (1890).

the granites, present various interesting types of more basic character in their peripheral and divergent portions.

The specific gravity of the syenites ranges between 2·7 and 2·9. Their variations in chemical composition are partly shown in the following table of analyses :—

| | I. | II. | III. | IV. | V. | VI. |
|---|---|---|---|---|---|---|
| $SiO_2$ | 59·83 | 62·52 | 65·43 | 61·28 | 56·90 | 62·58 |
| $Al_2O_3$ | 16·85 | 14·13 | 16·11 | 14·71 | 18·50 | 16·42 |
| $Fe_2O_3$ | ... | ... | 1·15 | 1·21 | 0·17 | 2·46 |
| FeO | 7·01 | 7·38 | 2·85 | 2·85 | 4·61 | 1·96 |
| MgO | 2·61 | 1·50 | 0·40 | 1·69 | 5·10 | 1·84 |
| CaO | 4·43 | 3·36 | 1·49 | 5·61 | 6·17 | 2·47 |
| $Na_2O$ | 2·44 | 6·25 | 5·00 | 2·99 | 2·99 | 4·57 |
| $K_2O$ | 6·57 | 3·05 | 5·97 | 7·70 | 4·14 | 3·91 |
| $H_2O$ | .. | ... | 0·58 | 0·71 | 0·51 | 1·78 |
| $TiO_2$ | ... | ... | 0·50 | 0·41 | 0·19 | 0·40 |
| $P_2O_5$ | ... | ... | 0·13 | 0·16 | 0·79 | 0·33 |
| $ZrO_2$ | ... | ... | 0·11 | SrO, 0·04 | ... | SrO, 0·10 |
| MnO | ... | ... | 0·23 | trace | trace | 0·08 |
| BaO | ... | ... | 0 03 | 0·72 | ... | 0·41 |
| $CO_2$ | ... | ... | trace ? | ... | ... | 0·77 |
| F | ... | ... | 0·08 | ... | ... | ... |
| Cl | ... | ... | 0·05 | ... | trace | ... |
| $FeS_2$ | ... | ... | 0·07 | ... | ... | ... |
| $SO_3$ | ... | ... | 0·08 | ... | ... | ... |
| Loss | 1·29 | 1·20 | ... | ... | ... | ... |
| | 101·03 | 99·39 | 100·18 | 100·16 | 100·07 | 100·08 |

I. From the Plauenscher-Grund, Dresden: coarse granular, with fresh pink orthoclase and black hornblende, some microscopic plagioclase, quartz and titanite; contains a trace of $T_iO_2$. Zirkel, *Poggend. Ann.* cxxxii. (1864), p. 622.

II. From Vetakollen, Norway: a pink fine-grained rock with orthoclase, a very little oligoclase and black hornblende. Kjerulf, 'Christiania Silur-becken.'

III. From Mount Ascutney, Vermont, United States. Analysed by Dr. Hillebrand, *B. U. S. G. S.* No. 168, p. 24: a syenite containing hornblende, augite, orthoclase, microperthite, plagioclase, biotite, quartz, magnetite, sphene, apatite and zircon.

IV. Augite-syenite, Turnback Creek, Tuolumne County, California. Analysed by H. N. Stokes, *op. cit.* p. 204: contains orthoclase and augite, with less plagioclase and quartz.

V. Augite-mica-syenite, Turkey Creek, Jefferson County, Colorado. Analysed by L. G. Eakins, *op. cit.* p. 140: contains orthoclase, augite, biotite, rhombic pyroxene, hornblende, plagioclase, quartz, apatite and magnetite. Sp. gr. 2·857.

VI. Syenite-porphyry from intrusive sheet near Yogo Peak, Montana. Analysed by Dr. Hillebrand, *op. cit.* p. 127; abundant phenocrysts of hornblende and orthoclase, with less biotite and plagioclase, in a ground-mass of alkali-felspar, with accessory quartz; also contains iron-ore and apatite, with secondary calcite, chlorite, sericite and kaolin.

**Orthophyre** (Quartz-less Orthoclase-porphyry) holds to the syenites a similar relation to that which the quartz-porphyries (felsites, aporhyolites) hold to the granites. It is composed of a compact brown, reddish, or grey ground-mass, mostly micro-crystalline but sometimes microlitic (felsitic), through which are usually scattered numerous crystals of orthoclase, sometimes also a triclinic felspar, black hornblende and glancing scales of dark biotite. It contains from 55 to 65 per cent of silica (see table on p. 220), thus differing from quartz-porphyry in its smaller proportion of this acid. It is also

rather more easily scratched with the knife, but except by chemical or microscopical analysis, it is often impossible to draw a distinction between this rock and its equivalents in the acid series. It occurs in veins, dykes, intrusive sheets and likewise in sheets of lava that have flowed out at the surface. It is met with in all these forms in the volcanic series of the Lower Old Red Sandstone in the south of Scotland.

A variety of this rock is the well-known Rhomben-porphyr of Southern Nôrway, which is distinguished by its large orthoclase or microcline crystals set abundantly in a fine-grained dark-grey ground-mass. Blocks of this easily recognisable material have been transported during the Glacial Period as far south as the coast of Norfolk.

**Keratophyre**—a term that has been variously used since first proposed by Gümbel in 1874, is best applied to a compact porphyritic rock in which the prevailing felspar is a soda-bearing species, instead of the ordinary orthoclase of the orthophyres. The silica percentage ranges between 60 and 70. Some varieties wherein quartz becomes conspicuous are called Quartz-keratophyre, and have sometimes as much as 75 or 80 per cent of silica. These may be regarded as soda-quartz-porphyries, and the ordinary keratophyres as soda-orthophyres. The difference between the composition of the two types is shown in the table, p. 220.

**Bostonite**—a fine-grained, highly-felspathic rock with a trachytoid structure and fracture, usually pale in colour, poor in dark minerals, but showing scattered crystals of orthoclase with a little plagioclase and sometimes a little quartz. Owing to its usually decomposed condition the constituents and structure of this rock are not always satisfactorily discernible. It occurs in dykes. The composition of a characteristic example is shown in the table, p. 220.

**Porphyrite**—a term formerly applied to ancient altered forms of andesite, is now generally restricted to rocks especially found in dykes, wherein a lime-soda felspar is predominant with a more or less marked porphyritic structure, large felspars being distributed through a fine ground-mass together with biotite, augite or hornblende. The term "Porphyry" as a suffix has been adopted by Rosenbusch and other petrographers in the sense already explained (p. 208).

**Lamprophyre.**—This general term now comprises a series of intrusive rocks that occur in dykes and sills composed of alkali-felspar and lime-soda felspar, black mica, hornblende, augite, magnetite, and apatite. Their structure is granular or compact. Owing to the frequent prevalence of black mica some of the series were originally known as "mica-traps." The rocks named Minette, Vogesite, Monchiquite, with their varieties, are classed as members of the Lamprophyre group.[1]

**Minette**—a close-grained to granular rock, with a ground-mass often exceedingly compact, through which are dispersed biotite, orthoclase, plagioclase, augite, apatite and iron-ore. The augite may be a pale green diopside. The mica has a characteristic minute structure seen under the microscope. In thin dykes the ground-mass presents a somewhat trachyte-like arrangement of felspar laths, but in thicker masses it becomes coarser and more indefinitely granular. Minette is one of the mica-traps frequently found as veins and other intrusive bodies.

**Kersantite**—distinguished by the abundance of dark mica crowded in its ground-mass, together with a good deal of augite, in the malacolitic form, but generally with little or no hornblende.

**Vogesite**—in this rock, while the greyish or black ground-mass consists of orthoclase, abundant phenocrysts of hornblende or augite are dispersed, these minerals taking here the prominent place that black mica does in the minettes. Under the microscope the alkali-felspar is found to be united with a small admixture of laths of plagioclase. The hornblende is likewise lath-shaped, so that, as in minette, a trachytoid structure is produced. The rock is another of the series of masses that occur intrusively in dykes.

[1] For an account of the Lamprophyres of the classical district of the Plauenscher-Grund, see R. Doss, *Tschermak's Mineral. Mittheil.* xi. (1889).

| | I. | II. | III. | IV. | V. | VI. | VII. |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 59·17 | 63·58 | 77·29 | 60·11 | 51·65 | 52·26 | 45·15 |
| $Al_2O_3$ | 19·73 | 13·60 | 14·62 | 19·01 | 13·89 | 13·96 | 15·39 |
| $Fe_2O_3$ | ... | 6·71 | trace | 4·63 | 2·70 | 2·76 | 2·76 |
| FeO | 1·71 | 4·77 | ... | 0·37 | 4·80 | 4·45 | 5·64 |
| MgO | 0·40 | 2·58 | 0·38 | 0·23 | 11·56 | 8·21 | 6·38 |
| SrO | ... | .. | ... | ... | ... | 0·05 | ... |
| CaO | 3·92 | ... | trace | 0·66 | 4·07 | 7·06 | 8·83 |
| $Na_2O$ | 3·54 | 5·25 | 7·60 | 6·53 | 2·99 | 2·80 | 2·67 |
| $K_2O$ | 4·03 | 0·32 | 0·16 | 5·36 | 4·15 | 3·87 | 2·77 |
| $Li_2O$ | ... | ... | ... | ... | ... | trace | trace |
| $H_2O$ | ... | 2·94 | 0·57 | ... | 3·19 | 2·87 | 2·85 |
| $TiO_2$ | ... | ... | ... | 0·96 | 0·55 | 0·58 | 2·80 |
| $P_2O_5$ | ... | ... | ... | ... | 0·21 | 0·52 | 0·56 |
| $Cr_2O_3$ | ... | ... | . | ... | 0·08 | trace | ... |
| MnO | ... | .. | ... | trace | 0·15 | 0·14 | 0·14 |
| BaO | ... | ... | ... | ... | 0·19 | 0·23 | ... |
| $SO_3$ | ... | ... | ... | ... | 0·19 | ... | ... |
| $CO_2$ | 2·52 | ... | ... | 0·84 | ... | 0 49 | 4·27 |
| Loss | 3·40 | ... | ... | 1·37 | ... | ... | ... |
| | 98·42 | 99·45 | 100·62 | 100·07 | 100·37 | 100·25 | 100·21 |

I. Orthophyre from Predazzo, Tyrol: vein of somewhat weathered rock showing pink orthoclase without quartz. Kjerulf, "Christiania Silurbecken" (1855).

II. Keratophyre from Rosenbühl, near Hof. Analysed by Loretz.

III. Quartz-keratophyre, near Rathdrum, County Wicklow. Analysed by Dr. F. V. Hatch

IV. Bostonite, Tutvet, Hedrum, Southern Norway. Analysed by Brögger.

V. Lamprophyre, Cottonwood Creek, Montana. Analysed by Chatard: an indeterminate ground-mass carrying augite, iron-oxides and mica, with porphyritic augite and olivine.

VI. Minette, Sheep Creek, Little Belt Mountains, Montana. Analysed by Hillebrand: taken from a fresh and rather coarse-grained rock.

VII. Vogesite, Fourmile Creek, Castle Mountain District, Montana. Analysed by Pirsson: contains augite, hornblende, iron-ore, a little plagioclase, orthoclase, calcite and some decomposition products; specific gravity, 2·70.

### iv. Elæolite (Nepheline)-Syenite Family.

In this family is comprised a series of rocks in which the alkali-felspar is accompanied by elæolite (nepheline), but where no excess of silica has crystallised out in quartz.

**Elæolite-syenite** (*Nepheline-syenite*), characterised by the association of the variety of nepheline known as elæolite with orthoclase, and with minor proportions of microcline, plagioclase, pyroxene, hornblende, biotite, sodalite, magnetite, titanic iron, zircon, sphene and other minerals. It is distinguished by the large number of minerals that occur in it or in the pegmatite dykes associated with it, and in which some of the rarer elements are combined, such as thorium, yttrium, cerium, lanthanum, tantalum, niobium, zirconium, &c. It is typically developed in Southern Norway (Brevig, Laurvig). The structure is sometimes coarse and granitic, with large rounded aggregates of felspar, elæolite and the bluish sodalite; sometimes it presents an assemblage of tabular or lath-shaped felspars between which the other two minerals are enclosed, and a more or less parallel arrangement is produced.

This intrusive rock has been typically developed in Southern Norway, where it has been studied in great detail by Brögger, who in his elaborate monograph supplies detailed

information regarding its geological relations, chemical composition, and more especially its remarkable accompaniment of pegmatite veins with their astonishing assemblage of minerals. The whole complex of intrusive material is shown to be later than Silurian time. Three types of structure have been distinguished in this material by Brogger: 1st, the chief rock, presenting the coarsest aggregate of minerals; 2nd, a medium-grained granular or granitic structure; and 3rd, a finer-grained diabase-like arrangement of the tabular felspars. The first of these types he has called Laurdalite, characterised by the hypidiomorphic arrangement of its large subparallel felspars and the abundance of its large hypidiomorphic kernels of elæolite.[1] From a half to two-thirds of the rock consists of cryptoperthite (soda-orthoclase) and soda-microcline (anorthoclase of Rosenbusch), with a little microperthite. The elæolite is frequently but not always accompanied by sodalite. Cancrinite occurs sparingly and appears to be a result of the alteration of the nepheline. The mica is lepidomelan, and comes next to the felspars and elæolite in abundance. Pyroxene appears sometimes like diallage, sometimes as diopside. Aegerine occurs sparingly in some varieties. The hornblende minerals are usually absent from the typical rock, as also is olivine.

Ditroite—a term which has been applied to several varieties of nepheline-syenite rocks, is restricted by Brögger to his second type, possessing a normal granitic (eugranitic) structure. In like manner he makes use of the term Foyaite, which was somewhat vaguely employed even for rocks which contain little or no nepheline, and applies it to his third type, which is marked by a trachytoid arrangement of the constituent minerals.[2]

Pulaskite—an acid rock relatively poor in alkalies, with little or no nepheline, has been classed with the nepheline-syenites, but passes into the syenites with soda.

Miaskite—a name taken from Miask in the Ilmengebirge, is applied to a coarse granitoid aggregate of orthoclase, elæolite, and black mica, the last mineral being specially characteristic.

Zircon-syenite, as the name denotes, is a variety rich in zircon.

Tinguaite—a rock with a fine-grained ground-mass, consisting of an aggregate of felspar, nepheline and aegerine, with some accessory mica and apatite, through which are dispersed crystals of soda-orthoclase, pyroxene, hornblende, dark mica, a good deal of nepheline filling interspaces, and apatite. It is one of the rocks found as dykes, and is well developed in Southern Norway, where it occurs as one of the series of intrusions connected with the syenite. A variety, distinguished as "leucite-tinguaite," has been described from different parts of the United States, especially Arkansas, New Jersey, and Montana. An example recently found as a dyke in the post-Cambrian elæolite-syenite of Sussex County, New Jersey, contains 50 per cent of silica, and is roughly estimated to be made up of pyroxene 22 per cent, nepheline 36, orthoclase 38, titanite, apatite, &c., 4.[3]

Sölvsbergite.—Under this name Brögger has described a number of rocks with little or no quartz, which form part of the great series of dykes in Southern Norway. They are of medium or fine grain, consisting chiefly of alkali-felspars (mostly albite and microcline) with aegerine; but in the more basic varieties carrying, instead of the aegerine, sometimes hornblende (*Katoforite*), sometimes also a peculiar mica; while in the most basic kinds the quartz disappears and nepheline is present. In chemical composition they stand between the highly quartziferous grorudites and the nepheline-bearing tinguaites.[4] An intrusive rock in the Crazy Mountains, Montana, has been

[1] 'Die Silur. Etage,' Christiania (1882), p. 278. 'Mineral Syenitpegmatitgäuge,' 1890, p. 32.

[2] Brögger, 'Die Silur. Etage,' ii. and iii. (1882), pp. 278-283. 'Die Eruptivgest-Kristianiageb.' iii. (1898), pp. 7, 162.

[3] J. E. Wolff, *Bull. Mus. Compar. Zool. Harvard*, xxxviii. (1902), p. 273.

[4] 'Eruptivgest. Kristianiageb,' i. (1894), p. 67.

described by Messrs. Wolff and Tarr under the name of Acmite-trachyte; it contains large porphyritic crystals of a triclinic felspar which enclose apatite, sodalite, augite, aegerine and biotite; also crystals of sodalite and augite in a ground-mass of trachytic type, composed essentially of slender lath-shaped felspars and acicular crystals of aegerine, with needles of acmite, and also apatite and magnetite.[1]

Borolanite—a rock associated with a large mass of igneous material which has disrupted and altered the Cambrian limestone of Loch Borolan, in the county of Sutherland.[2] It is of medium grain, dark-grey, with white patches, and consists of orthoclase, plagioclase, melanite, nepheline in an altered condition, pyroxene and biotite with apatite, sphene and iron-ores as accessary constituents. Its chemical constitution is shown in the table on p. 223. The rock is a member of the elæolite-syenite family, but is distinguished by the presence of black garnet (melanite) as an essential constituent.

Some eruptive rocks may perhaps be most conveniently placed here which do not fall naturally into any of the other families, but some of which may be taken as types of distinct families.

**Shonkinite**—a rather coarse-granular holocrystalline rock, composed essentially of orthoclase and augite, the latter mineral being so abundant as to form at least one-half of the mass by volume and a greater proportion by weight. The rock contains likewise smaller amounts of olivine and iron-ore, with accessory apatite, sodalite, nepheline, biotite, etc. It has been found and described by Messrs. Weed and Pirsson in the Highwood Mountains, Montana, from the Indian appellation of which (Shonkin) they have named it. They regard it as a distinct rock-type allied to the vogesites and minettes. Its composition is shown in the annexed table.

**Ijolite**—a granitoid rock consisting essentially of elæolite and pyroxene, first found in dykes in Finland and more recently in Arkansas. It consists largely of nephelite and pyroxene (diopside) with melanite, aegerine, titanite and apatite. At Magnet Cove, Arkansas, it forms one of a series of stages of differentiation.[3] It is allied in composition to the nephelinites.

**Malignite**—a name given by Professor A. C. Lawson to a family of rocks which form an intrusive mass in the Coutchiching schists of Poohbah Lake near the Maligne River, in the district of Rainy River, Province of Ontario, Canada. They are characterised as holocrystalline, with predominant orthoclase, having often an acid plagioclase in microscopic intergrowth, aegerine-augite as their constant ferromagnesian silicate, with biotite and a soda-amphibole. He distinguishes three types among them. (1) Nepheline-pyroxene-malignite (sp. gr. 2·879), resembling externally a felspathic dolerite, and composed of orthoclase, nepheline, apatite, abundant black pyroxene, occasional plates of brown biotite and rare grains of sphene, and having a silica percentage ranging from 47·63 to 49·15; alumina, 13·16 to 20·1; ferric oxide, 2·74 to 7·39; ferrous oxide, 0·8 to 5·88; lime, 5·4 to 15·70; magnesia, 1·1 to 5·75; potash, 3·68 to 7·1; and soda, 1·18 to 5·5. (2) Garnet-pyroxene-malignite, characterised by its prominent large thick plates of pale pink orthoclase imbedded in a parallel position in a dark green moderately fine-grained holocrystalline matrix, which is an aggregate of aegerine-augite, melanite, biotite, sphene and apatite. The specific gravity of the rock is 2·88. (3) Amphibole-malignite, differs from the last-named type in the smaller size of its orthoclase crystals, in the much coarser texture of the dark green to black matrix in which they are imbedded, and in the preponderance of a lustrous black amphibole in grains of large size.[4]

[1] *Bull. Mus. Compar. Zool. Harvard*, xvi. (1893), p. 227.

[2] Messrs. J. Horne and J. J. Teall, *Trans. Roy. Soc. Edin.* xxxvii. (1892), p. 163.

[3] H. S. Washington, "The Foyaite-Ijolite series of Magnet Cove: a Chemical Study in Differentiation," *Journ. Geol.* ix. (1901), p. 607.

[4] A. C. Lawson, *Bull. Geol. University, California*, vol. i. No. 12 (1896).

| | I. | II. | III. | IV. | V. | VI. | VII. | VIII. |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 54·55 | 56·45 | 55·50 | 56·58 | 64·92 | 60·20 | 47·8 | 46·73 |
| $TiO_2$ | 1·40 | 0·66 | 0·50[1] | ... | ... | 0·14 | 0·7 | 0·78 |
| $Al_2O_3$ | 19·07 | 21·97 | 22·45 | 19·89 | 16·30 | 20·40 | 20·1 | 10·05 |
| $Fe_2O_3$ | 2·41 | | 1·03 | 3·18 | 3·62 | 1·74 | 6·7 | 3·53 |
| FeO | 3·12 | 3·40 | 1·32 | 0·56 | 0·84 | 1·88 | 0·8 | 8·20 |
| MnO | 0·17 | | ... | 0·47 | 0·40 | trace | 0·5 | 0·28 |
| MgO | 1·98 | 1·19 | 0·47 | 0·13 | 0·22 | 1·04 | 1·1 | 9·68 |
| CaO | 3·15 | 2·22 | 1·60 | 1·10 | 1·20 | 2·00 | 5·4 | 13·22 |
| BaO | ... | ... | ... | ... | ... | trace | 0·8 | ... |
| $Na_2O$ | 7·67 | 7·37 | 10·47 | 10·72 | 6·62 | 6·30 | 5·5 | 1·81 |
| $K_2O$ | 4·84 | 5·87 | 5·48 | 5·43 | 4·98 | 6·07 | 7·1 | 3·76 |
| $H_2O$ (loss) | 0·72 | 0·45 | 0·96 | 1·77 | 0·50 | 0·33 | 2·4 | 1·24 |
| $P_2O_5$ | 0·74 | 0·28 | trace | ... | ... | 0·15 | ... | 1·51 |
| $SO_3$ | ... | ... | ... | ... | ... | 0·13 | 0·4 | ... |
| Cl | ... | ... | ... | .. | ... | 0·09 | ... | 0·18 |
| | 99·82 | 99·86 | 100·05 | 99·83 | 99·60 | 100·47 | 99·3 | 100·97 |

[1] And $ZrO_2$.

I. Typical Laurdalite, Löve, Longendal. Analysed by G. Forsberg: Brögger, 'Eruptivgest Kristianiageb,' Part iii. p. 19.
II. Typical Ditroite, Bratholmen, Landgangsfjord. Analysed by G. Forsberg: Brögger, *op. cit.* p. 167.
III. Aegerine-mica, Foyaite, Brathagen. Analysed by G. Forsberg: Brögger, *op. cit.* p. 176.
IV. Tinguaite, Hedrum. Analysed by G. Paykull: Brögger, *op. cit.*, Part ii. p. 113.
V. Sölvsbergite, from the typical locality at Sölvsberget. Analysed in laborat. L. Schmelk: Brögger, *op. cit.* p. 78.
VI. Pulaskite, from the type locality, Fourche Mountain, Little Rock, Arkansas. Analysed by H. S. Washington, *Journ. Geol.* ix. (1901), p. 609.
VII. Borolanite, Loch Borolan, Sutherland. Analysed by J. H. Player, *Trans. Roy. Soc. Edin.* xxxvii. (1892), p. 178.
VIII. Shonkinite, from the Highwood Mountains, Montana: Weed and Pirsson, *Bull. Geol. Soc. Amer.* vi. (1895), pp. 407-416.

### v. Diorite Family.

Under the general term Diorite is comprehended a group of rocks which, possessing a granitic structure, differ from the granites in their much smaller percentage of silica (though one section of them containing free quartz approaches the granites in composition), and from the syenites in containing plagioclase (chiefly a soda-lime felspar) instead of orthoclase as their chief constituent. Their second constituent is hornblende with various accessory minerals. They are sometimes divided into two sections, the quartz-diorites and the normal diorites. Many of these rocks were formerly included in the general division of "Greenstones," a word still employed by many field-geologists as a temporary designation for rocks which they encounter and have to trace before microscopic and chemical evidence is available to determine their true petrographical character.

**Quartz-diorite**—a holocrystalline granitoid mixture of a lime-soda-plagioclase (oligoclase, less frequently andesine or labradorite), quartz and hornblende, with generally a small proportion of orthoclase, biotite or augite, apatite or magnetite. It outwardly resembles grey granite, and, indeed, includes many so-called granites, but may usually be distinguished from them, even with the naked eye or with a lens, by the striated

faces of its felspars. Its silica ranges up to 67 per cent, and its specific gravity rises sometimes to 2·95. It is an eruptive rock which occurs in bosses and thick intrusive sheets or dykes.

**Diorite** (Normal Diorite).—This rock possesses the typical granitoid structure and consists of the same minerals as Quartz-diorite, except that the quartz is almost entirely absent. Hornblende and black mica occur together in some varieties, pyroxene characterises others (Augite-diorite), while in some biotite greatly preponderates (Mica-diorite). Under the microscope the thoroughly crystalline structure is well seen, and among the pyroxene-diorites the felspar and pyroxene are sometimes found to be intergrown in ophitic aggregates. The mean specific gravity is about 2·95, and the chemical composition is given in the table of analyses on the next page.

Among the varieties of diorite, the following may be mentioned. Diorite-porphyry—a microgranitoid ground-mass, plagioclase (in minute laths), alkali-felspar and quartz, with phenocrysts of hornblende, plagioclase, quartz and grains of iron ores. Corsite—a granitoid mixture of greyish-white plagioclase, blackish-green hornblende, and some quartz, which have grouped themselves into globular aggregations with an internal radial and concentric structure (Orbicular diorite, Kugeldiorit, Napoleonite—Fig. 7), typically developed in Corsica, whence the name, but found also in Scandinavia.[1] Tonalite (from Monte Tonale, Tyrol)—a quartz-mica-hornblende-diorite containing dihexahedral quartz, snow white plagioclase, hexagonal plates of black mica and stumpy prisms of blackish-green hornblende, in strongly contrasted colours.

**Aphanite.**—As the granites pass into fine grained quartz-porphyries, and the syenites into compact orthoclase-porphyries, so the diorites have their close-textured varieties, which are comprised under the general term Aphanite, divisible into *Quartz-aphanite* and *Normal aphanite*. The general characteristic of these rocks is that the constituent minerals become so minute as to disappear from the naked eye. They are dark heavy close-grained masses. They merge into the basic diabases (p. 233).

**Kersantite**—a more or less compact mica-diorite, through which porphyritic crystals of biotite, sometimes of large size, are dispersed. Orthoclase, pyroxene, and even a little quartz may be present. The rock is found in dykes and other intrusive forms.

**Porphyrite.**—This term has been already explained, but may be again mentioned here. As it is now applied to Palæozoic or older intrusive rocks composed mainly of plagioclase-felspar with hornblende or biotite or both these minerals, sometimes with a little quartz, crystals of orthoclase, augite and other minerals, some varieties in composition and structure approach the diorites, others come nearer to the andesites. Distinctive names are given to some of these varieties, as *Hornblende-porphyrite*, *Hornblende-mica-porphyrite*.

**Camptonite** (Basic Diorite, Porphyritic Diorite)—a name given by Rosenbusch to a group of dark dyke-rocks, having somewhat the aspect of basalt, with a compact ground-mass composed mainly of felspar microlites with small prisms of basaltic hornblende, a little biotite, green augite, apatite, titaniferous iron, and streaks of devitrified glass. Porphyritic crystals of hornblende occur, more rarely of felspar, while some varieties contain analcime.[2]

**Epidiorite**—Under this general term is included a group of rocks which have originally been pyroxenic eruptive masses, but, by metamorphism, have acquired a crystalline re-arrangement of their constituents, the pyroxene being changed into hornblende, often fibrous or actinolitic, the felspar becoming granular, and the whole rock having often acquired a more or less distinctly schistose structure. The dark intrusive sheets associated with the crystalline schists of the Scottish Highlands and

[1] N. O. Holst and F. Eichstadt, *Geol. Fören. Stockholm Förhandl.* vii. p. 184.

[2] Hawes, 'Mineralogy and Lithology of New Hampshire,' 1878, p. 160; *Amer. Journ Sci.* xvii. (1879), p. 147; Rosenbusch, 'Massige Gest,' p. 338; Brögger, 'Eruptivgest-Kristianiageb,' iii. p. 48.

the north of Ireland are largely epidiorites. Some of these rocks are quartziferous, but many of them belong to the basic series (p. 252).

TABLE SHOWING THE CHEMICAL COMPOSITION OF SOME MEMBERS OF THE DIORITE FAMILY.

| | I. | II. | III. | IV. | V. | VI. |
|---|---|---|---|---|---|---|
| $SiO_2$ | 63·97 | 62·18 | 50·73 | 48·73 | 64·49 | 41·94 |
| $Al_2O_3$ | 15·78 | 15·77 | 19·99 | 11·92 | 17·25 | 15·36 |
| $Fe_2O_3$ | 2·35 | 1·83 | 3·20 | 4·79 | 0·86 | 3·27 |
| $FeO$ | 1·87 | 2·44 | 4·66 | 4·56 | 2·42 | 9·89 |
| $MgO$ | 2·84 | 3·55 | 3·48 | 5·93 | 1·24 | 5·01 |
| $CaO$ | 3·71 | 4·13 | 8·55 | 9·24 | 3·79 | 9·47 |
| $Na_2O$ | 4·36 | 3·92 | 4·03 | 2·62 | 4·19 | 5·15 |
| $K_2O$ | 4·01 | 3·91 | 1·89 | 2·47 | 4·15 | 0·19 |
| $H_2O$ | 0·58 | 1·00 | 0·77 | 1·52 | 0·60 | ... |
| $TiO_2$ | 0·48 | 0·55 | 1·59 | 1·34 | 0·51 | 4·15 |
| $P_2O_5$ | 0·40 | 0·32 | 0·81 | 0·32 | 0·23 | ... |
| $MnO$ | 0·05 | trace | 0·05 | 0·36 | trace | 0·25 |
| $NiO$ | trace | ... | .. | ... | ... | ... |
| $SO_3$ | ... | trace | .. | 0·34 | . . | ... |
| $Cl$ | . . | 0·4 | ... | 0·11 | ... | ... |
| $BaO$ | ... | 0·43 | 0·27 | trace | 0·30 | ... |
| $SrO$ | ... | 0·16 | 0·11 | ... | 0·08 | ... |
| $Li_2O$ | ... | ... | trace | trace | trace | loss 3·29 |
| $CO_2$ | ... | ... | ... | 5·80 | ... | 2·47 |
| | 100·40 | 100·23 | 100·13 | 100·05 | 100·11 | 100·04 |

I. Quartz-mica-diorite, Hurricane Ridge, Absaroka Range. Analysed by W. H. Melville, *B. U. S. G. S.* No. 168, p. 94: rock described by Iddings in *Monograph* xxxii. Part ii.

II. Diorite-porphyry, Steamboat Mountain, Montana. Analysed by W. F. Hillebrand, *20th Ann. Rep. U. S. G. S.* Part iii. p. 517: rock described by Pirsson.

III. Diorite from main mass, Big Timber Creek, Crazy Mountains, Montana. Analysed by W. F. Hillebrand, *B. U. S. G. S.* No. 168, p. 122: contains biotite, augite, labradorite, quartz, orthoclase, apatite and magnetite.

IV. Kersantite, Big Horn Pass, Yellowstone. Analysed by Whitfield, *op. cit.* p. 110: rock described by Iddings (*Monograph* xxxii. Part ii.), contains hornblende, plagioclase, orthoclase, quartz, augite, biotite, magnetite, chlorite, calcite and apatite; the augite and hornblende partly decomposed.

V. Porphyrite from dyke in contact zone, Sweet Grass Creek, Crazy Mountains, Montana. Analysed by W. F. Hillebrand, *B. U. S. G. S.* No. 168, p. 120: contains brown hornblende, biotite and labradorite in a ground-mass of plagioclase, biotite and hornblende, with a little quartz and orthoclase.

VI. Camptonite, from the typical locality, Campton, New Hampshire. Analysed by Hawes.

## vi. TRACHYTE FAMILY.

**Trachyte**—a term originally applied to modern volcanic rocks possessing a characteristic roughness (τραχύς) under the finger, is now restricted to a group of compact, usually pale, but sometimes brown and even black porphyritic, frequently cellular, rocks, consisting essentially of sanidine, with more or less triclinic felspar, augite, hornblende, biotite and magnetite, sometimes with apatite and tridymite. They are distinguished from the rhyolites (quartz-trachytes) by the absence of free quartz, and

by the smaller proportion of vitreous or microlitic (micro-felsitic) ground-mass. The sanidine crystals present abundant steam-pores and glass-inclusions, as well as hornblende-microlites and magnetite. In some varieties, the ground-mass appears to be entirely composed of colourless microlites of orthoclase crowded together in what is known as "fluctuation-structure" (p. 131), together with needles and grains of the darker silicates and of magnetite; in others, minor degrees of devitrification can be traced, until the ground-mass passes into a glass (trachyte-glass). The trachytes have been grouped as *Augite-trachyte*, *Amphibole-trachyte*, and *Biotite-trachyte*. *Phonolitic-trachyte* is a variety in which some slight admixture of sodalite, aegerine or acmite may be detected in drusy cavities or only as microscopic constituents, thus somewhat approaching the phonolites. In like manner those dark varieties which show a marked proportion of triclinic felspar, and thus have some of the characters of andesites, are known as *Andesitic trachytes*. The specific gravity of normal trachyte is about 2·6. The chemical composition is shown in the following table.[1]

Trachyte is an abundantly diffused lava of Tertiary and post-Tertiary date. It occurs in most of the volcanic districts of Europe (Siebengebirge, Nassau, Transylvania, Bay of Naples, Euganean Hills); in the Western Territories of the United States;[2] in New Zealand. It also occurs among the Old Red Sandstone and Carboniferous volcanic rocks of Scotland.[3]

Domite (so named from the Puy-de-Dôme) is a porous loosely aggregated trachyte, having a microlitic ground-mass, through which are dispersed tridymite, sanidine, much plagioclase, hornblende, magnetite, biotite, and specular iron. Soda-trachyte is a name given to Pantellerite (*ante*, p. 213), a variety rich in oligoclase, found in Pantelleria.

**Phonolite** (Nepheline-trachyte)—a term suggested by the metallic ringing sound emitted by the fresh compact varieties ("Clinkstone" of older authors) when struck. It is now applied to a compact, grey or brown, quartzless mixture of sanidine and nepheline, usually with some hauyne, which may be accompanied, as accessory constituents, by pyroxene, hornblende, or mica. The rock is rather subject to decomposition, hence its fissures and cavities are frequently filled with zeolites. The rock often splits into thin slabs which can be used for roofing purposes (Porphyrschiefer, Hornschiefer). Occasionally it assumes a porphyritic texture from the presence of large crystals of sanidine, hornblende, or biotite. When the rock is partly decomposed and takes a somewhat porous texture, it resembles normal trachyte.[4]

It is a thoroughly volcanic rock, and generally of Tertiary date. It occurs sometimes filling the pipes of volcanic orifices, sometimes as sheets which have been poured out in the form of lava-streams, and sometimes in dykes and veins. It is extensively developed in Bohemia, the Hegau, and in Central France. Some of the great bosses

[1] On trachyte consult T. Mügge, *Neues Jahrb.* 1883, ii. p. 192; von Dechen, 'Geognost. Führ. Siebengebirg.' 1861, and 'Vulkan. Vordereifel,' 1886; von Richthofen, *Jahrb. Geol. Reichsanst.* Vienna, xi. p. 153; Szabo, *Z. D. G. G.* xxix. (1877), p. 635; Zirkel, 'Micro. Petrog.' p. 143; King, 'Explor. 40th Parallel,' i. p. 578.

[2] It would appear that much of what has been regarded as trachyte in Western America is andesite, consisting essentially of plagioclase, and not of sanidine. The normal trachytes are now described as hornblende-mica-andesites, and the augite-trachytes are hypersthene-augite-andesites, most of the rest being dacites, and some of them rhyolites. Hague and Iddings, *Amer. Jour. Sci.* xxvii. (1884), p. 456.

[3] *Trans. Roy. Soc. Edin.* xxxvii. p. 122, Presidential Address, *Q. J. G. S.* xlviii. (1892), p. 112, 'Ancient Volcanoes of Great Britain,' i. pp. 276, 379.

[4] Boricky, 'Petrograph. Stud. Phonolitgestein. Böhmens,' *Archiv Landesdurchforschung Böhmen*, 1874. G. F. Föhr, "Die Phonolite des Hegau's," *Verh. Phys. Med. Ges. Würzburg*, xviii. (1883). Fouqué and Michel-Lévy, 'Mineral. Micrograph.' Whitman Cross, *Bull. U. S. G. S.* No. 150.

or eruptive vents connected with the Lower Carboniferous trachyte lavas of Haddingtonshire have been determined by Dr. Hatch to be true phonolites.

With the phonolites may be classed Leucite-phonolite, where the felspathoid is leucite instead of nepheline, and Nosean-trachyte (Nosean-phonolite), or Hauyne-trachyte (Hauyne-phonolite), with nosean or hauyne taking the place of the felspar of ordinary phonolite.

**Trachyte-Glass.**—In regions where trachyte rocks are well developed, various vitreous forms of them may be observed. Thus in the islands of Ischia and Procida and in the neighbouring Phlegræan fields glassy forms of augite-trachyte occur both in the form of obsidian and of pumice, but chemical analysis shows them not to belong to the acid rhyolites. The following table gives the composition of some trachytic rocks :—

| | I. | II. | III. |
|---|---|---|---|
| $SiO_2$ . . . . | 57·73 | 57·86 | 60·77 |
| $Al_2O_3$ . . . . | 18·93 | 20·26 | 19·83 |
| $Fe_2O_3$ . . . . | 1·97 | 2·35 | 4·14 |
| $FeO$ . . . . | 1·92 | 0·39 | 2·43 |
| $MgO$ . . . . | 0·91 | 0·04 | 0·34 |
| $CaO$ . . . . | 2·78 | 0·89 | 1·63 |
| $Na_2O$ . . . . | 5·52 | 9·47 | 4·90 |
| $K_2O$ . . . . | 6·11 | 5·19 | 6·27 |
| $H_2O$ . . . . | 3·15 | 2·61 | 0·24 |
| $TiO_2$ . . . . | 0·33 | 0·22 | ... |
| $P_2O_5$ . . . . | 0·25 | 0·03 | ... |
| $ZrO_2$ . . . . | trace | 0·15 | ... |
| $Cr_2O_3$ . . . . | trace | ... | ... |
| $V_2O_3$ . . . . | 0·01 | ... | ... |
| $NiO$ . . . . | trace ? | ... | ... |
| $MnO$ . . . . | 0·06 | 0·21 | trace |
| $SrO$ . . . . | 0·09 | 0·04 | ... |
| $BaO$ . . . . | 0·16 | 0·09 | ... |
| $Li_2O$ . . . . | trace | trace | ... |
| $SO_3$ . . . . | ... | 0·06 | .. |
| S . . . . . | ... | 0·03 | ... |
| Cl . . . . . | ... | 0·08 | ... |
| F . . . . . | ... | ? | .. |
| $CO_2$ . . . . | 0·26 | none | ... |
| $FeS_2$ . . . . | 0·02 | ... | ... |
| | 100·20 | 99·7 | 100·55 |

I. Biotite-trachyte, Dyke Mountain, Yellowstone Park. Analysed by W. F. Hillebrand, *B.U.S.G.S.* No. 168, p. 98 : contains orthoclase, plagioclase, biotite and magnetite.

II. Phonolite, Black Hills, Dakota. Analysed by W. F. Hillebrand, *op. cit.* p. 84 : rock described by Whitman Cross, *op. cit.* No. 150, p. 191 : contains sanidine, nepheline, aegerine, nosean and sodalite, with accessory sphene, apatite and zircon, and possibly some rare zirconates or titanates.

III. Trachyte-glass, Ischia. Analysed by C. W. C. Fuchs, Zirkel, 'Lehrbuch,' ii. p. 400. This column may be taken as a fair type of the older style of analysis ; the other two columns illustrate the more detailed modern method.

Besides the rocks in the Trachyte family above enumerated others more or less divergent from the general type have received special names, and may be alluded to here. From his studies of the old Italian volcanic districts, Mr. H. S. Washington has introduced Vulsinite (and Biotite-vulsinite) to denote a group of rocks corresponding

to the trachy-dolerites of Abich and Hartung, and to some of the andesitic trachytes of Rosenbusch, and which he regards as effusive representatives of Brögger's abyssal monzonites.[1] Ciminite includes certain rocks intermediate between trachyte and andesite, but marked by their large amount of magnesia and the presence in them of olivine;[2] Toscanite—rocks resembling the two last groups in containing basic plagioclase as well as orthoclase, but differing from them in being more acid ($SiO_2$, 63 to 72 per cent), and even containing free quartz.[3] He classes these together with the Absarokite, Shoshonite and Banakite of Iddings (*postea*, p. 236) as a "Trachy-dolerite" series, which stands on the trachytic side of the andesites, while the basalts come on the other side.[4] Mr. Ransome has found among the lava-flows of the western slope of the Sierra Nevada, California, some further varieties, which he has grouped under the name of Latite, characterised by the occurrence of a (hyalopilitic) ground-mass of labradorite laths, grains of augite and a turbid globulitic glass through which are scattered phenocrysts of labradorite, augite and olivine. Their silica percentage ranges from 56·19 to 62·33.[5]

Leucite-trachyte—a dark-grey compact aphanitic ground-mass of andesitic structure, through which are scattered in profusion leucite crystals, making in places more than a third of the bulk of the rock: found in the Viterbo volcanic district.[6]

In Leucite-phonolite (p. 227) the leucite is sometimes altered into an aggregate of nepheline with orthoclase grains and crystals.[7]

### vii. Andesite Family.

The term Andesite, originally given by Von Buch to certain lavas found in the Andes, is now applied to a large series of rocks once grouped with the trachytes, but now distinguished from them by having plagioclase as their felspar, and by their more basic character, which connects them with the dolerites and basalts. In fresh examples they are dark grey, or even black, with a compact ground-mass, through which striated felspar prisms may generally be observed. They often assume cellular and porphyritic structures. At the one end of the series stand rocks containing free silica (Dacite), while at the other are basalt-like masses of much more basic composition (Augite-andesite). Under the microscope the ground-mass presents more or less of a pale brownish glass crowded with microlites or minute laths of felspar, so as to present a characteristic felted (hyalopilitic) appearance with a marked flow-structure. This "microlitic felt" is a distinctive character of the Andesites.

**Dacite** (Quartz-andesite)—composed mainly of plagioclase, quartz and mica, with a varying amount of sanidine as an accessory constituent, and, by addition of hornblende and pyroxene, graduating into hornblende-andesite. The ground-mass has a felsitic, sometimes spherulitic, glassy, or finely pumiceous base. The average specific gravity of the rock is between 2·5 and 2·6, and its chemical composition is shown in the table of analysis on p. 231. Dacite occurs intrusively and also as sheets of superficial lava. It has been observed in the Euganean Hills, also in Hungary and some other parts of Europe, but it is most extensively developed in the Great Basin and other tracts of western North America among Tertiary and recent volcanic outbursts.[8]

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[1] *Journ. Geol.* iv. (1896), p. 547; v. (1897), p. 250.

[2] *Op. cit.* p. 834.

[3] *Op. cit.* v. (1897), p. 37.

[4] *Op. cit.* p. 366.

[5] *Amer. Journ. Sci.* v. (1898), p. 355.

[6] H. S. Washington, "Italian Petrological Studies," No. II. *Journ. Geol.* iv. (1896), 840; v. (1897), p. 248.

[7] *Op. cit.* v. p. 43.

[8] Iddings, *Monograph* xx. *U. S. G. S.* p. 368.

**Hornblende-andesite**[1] consists of a triclinic felspar (especially labradorite or andesine), with hornblende, augite, mica, magnetite and apatite. The ground-mass resembles that of trachyte, presenting sometimes remains of a pale glass. The porphyritic minerals frequently show evidence of having been much corroded before consolidation. Hornblende-andesite is found among the Tertiary and post-Tertiary volcanic rocks of Hungary, Transylvania, Siebengebirge, and in some of the Western Territories of the United States. According to researches by Messrs. Hague and Iddings, gradations from this rock into basalt and hypersthene-andesite can be traced in California, Oregon, and Washington. These rocks, therefore, cannot be said to have sharply defined and distinct forms.[2] According to the predominance of the minerals, varieties are distinguished as hornblende-mica-andesite, mica-hornblende-andesite, and mica-andesite. Under the name of hornblende-mica-andesite American petrographers have described a frequent variety of rock throughout the Great Basin, characterised by the vitreous appearance of its felspar, its rough porous trachyte-like ground-mass, and the presence of mica as an essential constituent. This term will include a large proportion of the rocks hitherto classed as trachytes, but in which the felspar proves to be plagioclase and not sanidine.[3] The specific gravity of these rocks ranges between 2·5 and 2·7, their chemical composition is illustrated by the analysis in the following table (p. 231).

Trachytic Andesite is a name sometimes given to andesites in which the ground-mass resembles that of trachyte in structure, with phenocrysts of triclinic felspar, hornblende, biotite and pyroxene. The intimate relation of the two families of rocks is further shown by the use of such a term as andesite trachyte.[4]

**Pyroxene-andesite**—includes dark heavy basalt-like rocks, with a compact or finely crystalline, sometimes more or less distinctly vitreous, ground-mass which under the microscope presents the characteristic microlitic felt, and through which are usually dispersed phenocrysts of labradorite or oligoclase, with augite and abundant magnetite, sometimes with olivine, hornblende or mica (Augite-andesite). The specific gravity of these rocks is from 2·5 to 2·7, and their chemical composition is indicated by the analysis in the following table.

It was formerly supposed that the pyroxene of the andesites was always augite. But rhombic forms of the mineral have now been frequently detected. Under the name of Hypersthene-andesite, certain Tertiary or recent rocks, stretching over vast areas in Western America, have been described as associated with other andesites and basalts. They are black to grey, or reddish-grey, in colour, and vary in texture from dense, thoroughly crystalline forms, to others approaching white glassy pumice, the base under the microscope ranging from a brown glass to a holocrystalline structure. The magnesian silicate is pyroxene, chiefly in the orthorhombic form as hypersthene, but partly also as augite. An analysis of the pumiceous form of the rock gave 62 per cent of silica, while the percentage of the same constituent in the glass of the base was found to rise to 69·94.[5] While the Dacites have affinities with the Rhyolites, and the Hornblende-andesites with the Trachytes, the Pyroxene-andesites approach the basalts in composition and mode of occurrence.

The older forms of pyroxene-andesite are generally more or less decayed, and appear

[1] See Zirkel, 'Microscop. Petrog.' p. 122. King, in vol. i. of 'Explor. 40th Parallel,' p. 562. Hague and Iddings, *Amer. Journ. Sci.* xxvi. (1883), p. 230.

[2] *Amer. Journ. Sci.* Sept. 1883, p. 233.

[3] Hague and Iddings, *Amer. Journ. Sci.* xxvii. (1884), p. 460. Iddings, *Monograph* xx. *U. S. G. S.* p. 364.

[4] For an illustration see C. Riva, 'Sulle Trachiti-andesitiche della Tolfa,' Milan, 1898.

[5] Whitman Cross, *Bull. U. S. G. S.* 1883, No. 1. Hague and Iddings, *Amer. Journ. Sci.* xxvi. (1883), p. 226; xxvii. (1884), p. 457. Iddings gives a detailed description of the pyroxene-andesites of the Eureka district in *Monograph* xx. *U. S. G. S.* pp. 348-364.

as dull sometimes earthy, generally reddish or brownish rocks. These altered types were formerly grouped under the name of Porphyrite. They are now identified as undoubtedly decayed forms of andesite, usually of pyroxene-andesite. When freshest they are dark grey or black, sometimes even preserving a pitchstone-like ground-mass. They are commonly porphyritic, and show abundant scattered crystals of plagioclase, less commonly of mica. Their texture varies from coarse crystalline to exceedingly close-grained, passing occasionally into vitreous varieties (Yetholm, Cheviot Hills). Rocks of this type have been abundantly poured forth as lavas during Palæozoic time, and they occur as interstratified lava-beds, eruptive sheets, dykes, veins, and irregular bosses. In Scotland they form masses, several thousand feet thick, erupted in the time of the Lower Old Red Sandstone, and others of wide extent and several hundred feet in depth belonging to the Lower Carboniferous period. In Germany "porphyrites" appear also at numerous points among formations of later Palæozoic age.

Pyroxene-andesite occurs in dykes, lava-streams, plateaux, sheets, and neck-like bosses in regions of extinct and active volcanoes, as in the volcanoes of the East Indies, Inner Hebrides, Antrim, Transylvania, Hungary, Santorin, Iceland, Teneriffe, the Western Territories of North America,[1] the Andes, New Zealand, &c. Many of the rocks of these regions now classed under this name were long known and described as dolerites and basalts. Indeed, there is the closest relation between them and the true olivine-bearing dolerites and basalts. The latter occur among the Tertiary volcanic plateaux of Britain, interstratified with rocks which, not containing olivine, have been placed among the andesites. Neither in their mode of occurrence nor to the eye in hand specimens is there any good distinction to be drawn between them. But the andesites are chemically less basic, and they present the characteristic microlitic felt under the microscope which differs from the structure of the dolerites and basalts.

**Propylite**—a name given by Richthofen to certain Tertiary volcanic rocks of Hungary, Transylvania, and the Western Territories of the United States, consisting of a triclinic felspar and hornblende in a fine-grained non-vitreous ground-mass, and closely related to the Hornblende-andesites. Their distinguishing feature is the great alteration which they have undergone, whereby their ferro-magnesian constituents have been converted into chlorite, and their felspars into epidote. Some quartziferous propylites have been described by Zirkel from Nevada, wherein the quartz abounds in liquid inclusions containing briskly-moving bubbles, and sometimes double enclosures with an interior of liquid carbon-dioxide.[2] A specimen from Storm Canon, Fish Creek Mountains, contained silica, 60·58; alumina, 17·52; ferric oxide, 2·77; ferrous oxide, 2·53; manganese, a trace; lime, 3·78; magnesia, 2·76; soda, 3·30; potash, 4·46; carbonic acid, a trace. Loss by ignition, 2·25; specific gravity, 2·6 to 2·7. The geologists of the Geological Survey of the United States believe that the rocks included under the term "propylite" in the western parts of America represent various stages of the decomposition of granular diorite, porphyritic diorite, diabase, quartz-porphyry, hornblende-andesite, and augite-andesite.[3] The name has been more recently applied by Rosenbusch and others to rocks which have undergone alteration by solfataric action.[4]

[1] Pyroxene-andesites are largely developed in California, where they have been studied by Professor A. C. Lawson and Mr. C. Palache. *Bull. Geol. Univ. California*, ii. No. 12 (1902), p. 411.

[2] Zirkel's 'Microscopical Petrography,' p. 110. King, 'Exploration of 40th Parallel,' i. p. 545. C. E. Dutton's "High Plateaux of Utah" (*U. S. Geographical and Geological Survey of the Rocky Mountains*), chaps. iii. and iv. Hague and Iddings, *Amer. Journ. Sci.* 1883.

[3] G. F. Becker on the Comstock Lode, *Reports of U. S. Geological Survey* 1880-81, and his full memoir in vol. iii. of the *Monographs of U. S. Geol. Survey* (1882). Hague and Iddings, *Amer. Journ. Sci.* xxvii. (1884), p. 454.

[4] Judd, *Q. J. G. S.* xlvi. (1890), p. 341. See Propylitisation, *postea*, p. 772.

CHEMICAL COMPOSITION OF ANDESITES.

| | I. | II. | III. |
|---|---|---|---|
| $SiO_2$ | 68·72 | 61·58 | 60·16 |
| $Al_2O_3$ | 15·15 | 16·96 | 15·34 |
| $Fe_2O_3$ | 1·16 | 1·75 | 3·07 |
| $FeO$ | 1·76 | 2·85 | 2·18 |
| $MgO$ | 1·28 | 3·67 | 3·41 |
| $CaO$ | 3·30 | 6·28 | 5·79 |
| $Na_2O$ | 4·26 | 3·94 | 3·88 |
| $K_2O$ | 2·78 | 1·28 | 2·59 |
| $H_2O$ | 0·74 | 1·30 | 2·04 |
| $TiO_2$ | 0·31 | 0·49 | 0·84 |
| $P_2O_5$ | 0·09 | 0·22 | 0·46 |
| $ZrO_2$ | ... | .. | 0·01 |
| $Cr_2O_3$ | ... | ... | trace ? |
| $NiO$, $CoO$ | ... | ... | trace |
| $MnO$ | 0·11 | trace | 0·08 |
| $SrO$ | 0·03 | trace | 0·08 |
| $BaO$ | 0·07 | 0·03 | 0·14 |
| $Li_2O$ | trace | trace | trace |
| $SO_3$ | ... | . . | 0·08 |
| S | ... | ... | trace |
| Cl | .. | . | undet. |
| F | ... | ... | undet. |
| | 99·76 | 100·35 | 100·15 |

I. Dacite, north-west base of Lassen Peak, California. Analysed by W. F. Hillebrand: contains quartz, felspar, biotite and hornblende, imbedded in a clear pumiceous glass, *B.U.S.G.S.* No. 168, p. 180, and Diller, No. 150, p. 218.

II. Hornblende-andesite, east side of Mount Shasta. Analysed by H. N. Stokes: contains small crystals of plagioclase and hornblende in a dark ground-mass, *B.U.S.G.S.* No. 168, p. 176.

III. Pyroxene-andesite, Sierra Grande, Colfax County, New Mexico. Analysed by W. F. Hillebrand: contains augite, less hypersthene, microliths of plagioclase, apatite, magnetite and a smoky-brown glassy base. *Op. cit.* p. 171, described by Whitman Cross, *op. cit.* p. 171.[1]

## viii. GABBRO, DOLERITE AND BASALT FAMILY.

We now enter upon the consideration of an interesting series of rocks distinguished by their low silica percentage, and the relative abundance of their basic constituents. A similar range of structure can be traced in them as in the acid and intermediate series already described. At the one extreme come rocks with a holocrystalline structure like the gabbros, passing into others of a hemi-crystalline character (dolerites) where, amid abundant crystals, crystallites and microlites, there are still traces of the original glass, and then graduating into types where the texture is still closer, with more abundant ground-mass and often a more basic composition (basalts), until at the other end come true basic volcanic glasses, which externally might be mistaken for the pitchstones and obsidians of the acid rocks. The more coarsely crystalline (holocrystalline) varieties are almost always intrusive in bosses, sills or dykes. Those of closer texture are often found as superficial lavas as well as in intrusive forms.

[1] On the chemical composition of the Andesites see a suggestive paper by Professor Iddings on "The Volcanic Rocks of the Andes," *Journ. Geol.* i. (1893), pp. 164-175.

**Gabbro**[1]—a group of coarsely crystalline rocks composed of plagioclase (labradorite or anorthite), pyroxene, frequently olivine, and also magnetite or titaniferous iron. The pyroxene in the normal gabbros is diallage or augite, but may be a rhombic species. Hornblende or mica may also be present. Occasionly free quartz is visible. These minerals occur in allotriomorphic forms, as in granite; but they sometimes assume ophitic relations which lead into the rock termed Dolerite. The felspar has often lost its vitreous lustre and passed into the dull opaque condition known as saussurite, when the rock has been called Saussurite-gabbro or Euphotide. The diallage is distinguished by its schiller-spar lustre. Some gabbros include a little metallic iron, the minute grains of which are revealed by being coated with copper when exposed to an acid solution of cupric sulphate.

While the structure is on the whole granitoid, some gabbros present a banded arrangement of their component minerals, the white felspar alternating with dark layers of the iron-ores or ferro-magnesian constituents, so as to present a strong resemblance to the internal structure of gneiss (p. 256 and papers there cited).

Various types of gabbro are distingushed by special names. Those in which the pyroxene is a rhombic form are termed Norite (Hypersthenite, Hyperite, Schillerfels). The more acid varieties are known as Quartz-gabbro and Quartz-norite. Where olivine becomes marked it gives rise to Olivine-gabbro and Olivine-norite—granitoid or ophitic compounds of plagioclase, olivine, pyroxene and magnetic or titaniferous iron. When the pyroxene disappears the rock becomes Troctolite (Forellenstein)—a mixture of white anorthite with dark-green olivine, which receives its name from the supposed resemblance of its speckled appearance to that of the side of a trout. When the olivine is absent the compound is a Pyroxene-rock (Augite-rock, Diallage-rock). Where both the ferro-magnesian constituents become greatly reduced or fail, the rock, which then consists of a mass of pale felspar, is tremed Labrador-rock (Labradorfels, Anorthosite).[2] Occasionally hornblende appears, either over and above the pyroxene, or as a result of the alternation of the latter, when the compound is known as Hornblende-gabbro.

The specific gravity of the gabbros ranges between 2·85 and 3·10. Their chemical composition varies with the changes in the proportions of their mineral constituents, but may be gathered from the analyses in the table on p. 239.

Theralite—a name given by Rosenbusch to a family of his "Tiefengesteine," embracing neo-volcanic effusive rocks mainly composed of a mixture of plagioclase and nepheline, with augite sometimes olivine or hornblende; to which biotite, apatite and iron-ores may be added.[3]

[1] On Gabbro see Lossen, *Z. D. G. G.* xix. p. 651. Lang, *op. cit.* xxxi. p. 484. Zirkel on Gabbros of Scotland, *op. cit.* xxiii. 1871. Judd, *Q. J. G. S.* xliii. (1886), p. 49. G. H. Williams, *Bull. U. S. G. S.* No. 28 (1886); *Amer. Geol.* vi. (1890), p. 35. F. D. Chester, *Bull. U. S. G. S.* No. 59 (1890). M. E. Wadsworth, *Geol. Surv. Minnesota*, Bull. 2, 1887. A. N. Winchell has published a detailed study of the gabbroid rocks of Minnesota, *Amer. Geol.* xxvi. (1900), pp. 151, 197, 261, 348. W. S. Bayley (*Journ. Geol.* i. 1893, p. 435) has given an interesting 'History of the Classification of the Gabbros and nearly related Rocks.' The banded arrangement of gabbros has been described by Lossen, *Z. D. G. G.* xliii. 1891, p. 533; A. G., *Trans. Roy. Soc. Edin.* xxxv. (1888); *Q. J. G. S.* l. (1894), pp. 212, 645; *Compt. rend. Cong. Géol. Internat.* Zurich, 1897; Elftmann. *Geol. Nat. Hist. Surv. Minnesota*, 23rd Rep. (1894), p. 224; A. Lacroix, *Bull. Cart. Géol. France*. No. 67 (1899), p. 89; H. W. Fairbanks, *Bull. Geol. Univ. California*, ii. (1896), p. 78; Loewinson-Lessing, *Trav. Soc. Nat. St. Petersb.* xxx. No. 5 (1900). Compare also J. P. Iddings, *Monog. U. S. G. S.* No. xxxii. Part ii. p. 67, where a banded structure in dacite-porphyry is noticed. The analogy of the banded structure of some gabbros to that of ancient gneisses is remarkably close. (Book IV. Part VIII. § ii.)

[2] On the Anorthosites of the Minnesota coast of Lake Superior, see A. C. Lawson, Bull. No. 9, *Geol. Nat. Hist. Surv. Minnesota* (1893).

[3] These rocks were first described by J. E. Wolff from the Crazy Mountains, Montana.

**Dolerite**—an important group of basic rocks, which connect the gabbros with the basalts and include many of the rocks once termed "Greenstones." They are composed of labradorite (or anorthite), with some ferro-magnesian mineral (augite, enstatite, olivine or mica) and magnetic or titaniferous iron. As a rule, they are holocrystalline, the constituent felspar and pyroxene or olivine being characteristically grouped in ophitic structure, but a little residual glass may occasionally be detected. They occur in bosses, sills and dykes, especially as the subterranean accompaniments of the volcanic action which has thrown out augite-andesites and basalts to the surface, but seldom as superficial lavas. Their specific gravity averages from 2·75 to 2·96. Their chemical constitution is indicated in the table on p. 239.

Different names have been proposed for the chief varieties of these rocks. The most important are Olivine-dolerite—a dark, heavy, close-grained finely-crystalline rock, with scattered olivine, apt to weather with a brown crust. Olivine-free dolerite—a similar rock but containing no olivine. Enstatite-dolerite contains enstatite in addition to the other ingredients. Nepheline-dolerite has the felspar largely or entirely replaced by nepheline (see p. 237).

**Diabase.**[1]—This term has been employed in various different senses. Under it is here placed a group of pyroxenic rocks which appear to depend for some of the most marked of their peculiarities upon their antiquity and the consequent alteration which they have undergone. They are dark green or black rocks found in older geological formations, and consist essentially of triclinic felspar, augite, magnetite or titaniferous iron, apatite, sometimes olivine, usually with more or less of diffused greenish chloritic substances (viridite) which have resulted from the alteration of the augite or olivine. Some carbonate of lime is usually present as a decomposition-product. The rocks thus agree generally in composition with the dolerites, allowance being made for the varying amount of alteration. Like these rocks they may be subdivided into diabase without olivine (normal diabase), but in the more acid varieties with a little free quartz, and olivine-diabase. Some varieties have been distinguished as enstatite-diabase, in which a rhombic pyroxene is present. The diabases generally possess an ophitic structure, the felspar crystals being enclosed within the augite. Their specific gravity is about 2·9, and their chemical composition is illustrated by one of the columns in the next table of analyses.

As in ordinary dolerite, gradations may be traced from coarsely crystalline diabase[2] into exceedingly fine-grained and compact varieties (Diabase-aphanite), which sometimes assume a fissile character (Diabase-schiefer) where they have been subjected to crushing or cleavage. Some kinds present a porphyritic structure, and show dispersed crystals of the component minerals (Diabase-porphyry, Labrador-porphyry, Augite-porphyry); or, as in some varieties of diorite, a concretionary arrangement is produced by the appearance of abundant pea-like bodies of a compact material, imbedded in a compact or finely crystalline ground-mass (Variolite[3]). When the green compact ground-mass contains small kernels of carbonate of lime, sometimes in great numbers, it is called Calcareous aphanite or Calcaphanite. Sometimes the rock is abundantly amygdaloidal. Though, as a rule, free silica does not occur in it, some varieties found to contain this mineral, possibly a secondary product, have been distinguished as

[1] The student will find in the *Zeitsch. Deutsch. Geol. Ges.* 1874, p. 1, an important memoir by Dathe on the composition and structure of diabase. See also 'Die Diabase des Oberen Ruhrthals.' A. Schenck, Inaug. Dissert. *Verh. nat. Verein. Rhein. Westphal.* 1884. H. Bäckström, 'Ueber fremde Einschlüsse in einigen Skandinavischen Diabasen,' *Bihang. Svensk. Vet. Akad. Handl.* xvi. (1890), ii. No. 1. The bibliography of diabase is fully given in the text-books of Zirkel and Rosenbusch.

[2] Michel-Lévy, *B. S. G. F.* 3rd ser. xi. p. 282. A. G., *Trans. Roy. Soc. Edin.* xxxi. p. 487.

[3] See on Variolite, G. A. J. Cole and J. W. Gregory, *Q. J. G. S.* xlvi. (1890), p. 295.

Quartz-diabase. A variety containing hornblende is termed Proterobase. Ophite, a variety occurring in the Pyrenees, contains diallage and epidote (p. 153). Further points of connection with the dolerites and basalts are furnished by the occasional occurrence of a pitchstone structure in diabase,[1] and by the rare inclusion of analcite among the crystalline constituents of the rock.[2]

Diabase occurs both in contemporaneous beds and in bosses, dykes and sills. Probably the Epidiorites noticed on p. 224 were formerly sheets and dykes of material like diabase, before the conversion of their pyroxenic constituent into hornblende.

Anamesite—a name given by Leonhard in his 'Basaltgebilde' (1832) to those members of the family in which the constituents are for the most part too minute to be recognised by the naked eye, and which therefore occupy a middle place between the more coarse-grained dolerites and the more compact basalts. The term is now seldom used.

Fig. 31.—Microscopic Structure of Basalt (magnified). The large shaded crystals are Olivine considerably serpentinised: the numerous small white prisms are Plagioclase. A few Augite prisms occur which, to the right of the centre of the drawing, are aggregated into a large compound crystal. The black specks are Magnetite.

**Teschenite**—a name first applied to some rocks in the Cretaceous system of Silesia and Moravia, consisting of plagioclase, brown amphibole, green or pink augite and a large admixture of analcime. They have been subdivided into at least two groups, one of which is placed with the diabases, while the other appears to be specially characterised by a mixture of plagioclase and nepheline.[3] Augite-teschenite has been described from California, where it was first called analcite-diabase.[4]

**Basalt**[5]—a group of black, extremely compact, apparently homogeneous rocks, which break with a splintery or conchoidal fracture, and in which the component minerals can only be observed with the microscope, unless where they are scattered porphyritically through the mass (Fig. 31). The minerals consist of plagioclase (labradorite or anorthite), pyroxene (usually augite, but occasionally a rhombic form), olivine, magnetite or titaniferous

[1] B. K. Emerson, *Bull. Geol. Soc. Amer.* viii. (1897), p. 59.

[2] H. W. Fairbanks on Analcite-Diabase, *Bull. Geol. Univ. California*, i. No. 9 (1895).

[3] C. E. M. Rohrbach, *Tschermak's Mittheil.* vii. (1885), p. 1. This author gives as the primary constituents of these rocks plagioclase, augite, hornblende, biotite, olivine, apatite, titaniferous iron, magnetite, orthoclase? and titanite. Among the secondary elements he reckons analcime, natrolite, apophyllite and other zeolites. The occurrence of analcite as an original constituent of some basic rocks in the United States seems to be now tolerably certain (p. 238).

[4] H. W. Fairbanks (*Bull. Geol. Univ. California* ii. 1896, p. 19), who regards the analcime of the rock as a secondary product after nepheline.

[5] On basalt rocks see K. C. v. Leonhard, 'Die Basaltgebilde,' 2 vols. 1832. Zirkel's 'Basaltgesteine,' 1870. Boricky's 'Petrographische Studien an den Basaltgesteinen Böhmens,' in *Archiv für Naturwiss. Landesdurchforschung von Böhmen*, ii. 1873. Allport, *Q. J. G. S.* xxx. p. 529. Möhl, *Nov. Act. Acad. Leop. Carol.* xxxvi. (1873), p. 74; *Neues Jahrb.* 1873, pp. 449, 824; 1879, p. 897. F. Eichstadt on Basalts of Scania, *Sveriges Geol. Undersök*, ser. c. No. 51, 1882. E. Svedmark, *op. cit.* No. 60, 1883. J. W. Judd, *Q. J. G. S.* xlii. (1886). A. G., *Trans. Roy. Soc. Edin.* xxxv. (1888), 'Ancient Volcanoes of Britain,' chaps. xxvi. and xxxvi. A. Helland, *Z. D. G. G.* xxxi. (1879), p. 720. Osann, *Neues Jahrb.* i. (1884), p. 44.

iron. Many years ago, Andrews detected native iron in the basalt of Antrim. More recently Nordenskiöld found this substance at Disco Island, in large blocks like meteorites (*ante*, p. 93), and in smaller pieces abundantly diffused through the Tertiary basalt. The ground-mass of the basalts presents under the microscope traces of glass in which are imbedded minute granules, hairs, needles, and microlites of felspar and augite. The proportion of this base varies within wide limits, insomuch that while in some parts of a basalt it so preponderates that the individual crystals are scattered widely through it, or are drawn out into beautiful streaks and eddies of fluxion structure, in others it almost disappears, and the rock then appears as a nearly crystalline mass, which thus graduates into dolerite and basic andesite. The component minerals frequently appear porphyritically dispersed, especially the olivine, the pale yellow grains of which are characteristic.

The normal Basalts or Felspar Basalts are susceptible in Central Scotland of subdivision into two groups, those which contain olivine and those which do not.[1] They thus agree with the range of composition of the dolerites. There is indeed the closest connection between basalt and dolerite, the difference being one of structure arising from the circumstances under which the magma cooled and consolidated. The basalts represent on the whole the superficial outflows and injected dykes of the magma, while the dolerites in large measure belong to the more subterranean (hypabyssal) portions of the same material.

Two types of basalt have been recognised in the great basaltic outbursts of Western America: (1) the porphyritic, consisting of a glassy and microlitic or micro-crystalline ground-mass, bearing relatively large crystals of olivine, felspar, and occasionally augite, a structure showing close relations to that of many andesites; (2) the granular (in the sense in which that term is used by Rosenbusch (p. 130, *note*))—an aggregate of quite uniform grains, composed of well-developed plagioclase and olivine crystals, with ill-defined patches of augite, and frequently with a considerable amount of glass-base. By diminution of olivine and augmentation of silica, and the appearance of hypersthene, gradations can be traced from true olivine-basalts into normal andesites. Basalts with free quartz are not infrequent in various regions of Western America.[2]

Basalt occurs in amorphous and columnar sheets, which may alternate with each other or with associated tuffs. It also forms abundant dykes, veins, and intrusive bosses. It frequently assumes a cellular structure, which becomes amygdaloidal by the deposit of calcite, zeolites, or other minerals in the vesicles. A relation may be traced between the development of amygdales and the state of the rock; the more amygdaloidal the rock, the more it is decomposed, whence the inference has been drawn that the amygdales have probably in large measure been derived by infiltrating water from the basalt itself. There can be no doubt, however, that at least in some cases the infilling of the vesicles with zeolites, &c., has taken place during the volcanic period, perhaps from the action of hot water charged with mineral solutions.[3]

Vitreous Basalt (Basalt-glass, Tachylyte, Hyalomelan).[4]—Basalt passes into a

[1] A. G., 'Ancient Volcanoes of Britain,' i. p. 418.

[2] Hague and Iddings, *Amer. Journ. Sci.* xxvi. (1884), p. 456. Iddings, *op. cit.* xxxvi. (1888), p. 208, *Bull. U. S. G. S.* Nos. 66 and 79. J. S. Diller, *Amer. Journ. Sci.* xxxiii. (1887), p. 45. The occurrence of quartz in basaltic and many lamprophyric rocks has been noted in different parts of Europe, but the grains with their signs of corrosion have generally been regarded as foreign materials derived from the explosion of sandstone or similar rocks through which the igneous rock has risen. (See Zirkel, 'Lehrbuch,' ii. p. 891.) The grains in some at least of the American examples would rather seem, however, to be original constituents. On the quartz-basalts of the the Permian (?) volcanic necks of Scotland, see A. G., 'Geology of Eastern Fife,' in *Mem. Geol. Surv. Scotland*, 1902.

[3] 'Ancient Volcanoes of Britain,' ii. p. 189.

[4] F. Rutley, *Journ. Roy. Geol. Soc. Ireland*, iv. Part iv. (1877), p. 227. See Judd and

condition which, even to the naked eye, is recognisable as that of a true glass. This more especially takes place along the edges of dykes and intrusive sheets. Where an external skin of the original molten rock has rapidly cooled and consolidated, in contact with the rocks through which the eruption took place, a transition can be traced within the space of less than a quarter of an inch from a crystalline dolerite, anamesite, basalt, or andesite into a black glass, which under the microscope assumes a pale brown or yellowish colour, and is isotropic, but generally contains abundant microlites, sometimes with a globular, spherulitic, or perlitic structure. In such cases it seems indisputable that this glass represents what was the general condition of the whole molten mass at the time of eruption, and that the present crystalline structure of the rock was developed during cooling and consolidation. The glassy forms of basalt undergo alteration into a yellowish substance called Palagonite (p. 174). It is worthy of remark that in the analyses of vitreous basalts, the percentage of silica rises usually above, while their specific gravity falls below, that of ordinary crystalline basalt.

The basalts are the heaviest members of the family to which they belong, their specific gravity ranging between 2·85 and 3·10. Their chemical composition is indicated on the following table of analyses (p. 239). Thoroughly volcanic in origin, and appearing in lava-streams, plateaux, sills, necks, dykes, and veins, they display the columnar structure so commonly among their finer-grained varieties that the term "basaltic" has been popularly used to denote it. It is found both in surface-lavas and in injected masses. Among the Tertiary basaltic plateaux of the Inner Hebrides the columns are often smaller and more curved and irregular than in the sills and dykes. As already stated, it has been assumed by some writers that basalt did not begin to be erupted until the Tertiary period. But true basalt occurs abundantly in Scotland as a product of Lower Carboniferous volcanoes, and exhibits there a variety of types of minute structure.[1]

Basic Pumice.—Though the acid lavas furnish most of the pumice with which we are familiar, some of the basic kinds also assume a similar structure. Thus at Hawaii, the basic pyroxenic or olivine lavas give rise to a pumiceous froth.

Melaphyre.—A place may be found here for a consideration of this term, which probably has been more diversely employed than any other in petrographical literature. Originally proposed by Brongniart, it has subsequently been applied in various senses by different writers to include rocks which range in structure and composition from the more basic andesites to true olivine-basalts, and which for the most part belong to pre-Tertiary eruptions (though some Tertiary lavas have been described as melaphyre). These rocks are essentially basalts which, owing to their long exposure, have undergone more or less alteration. If the term is to be retained as a definite rock-name it should be restricted to an altered type, and preferentially to the older altered basalts. The melaphyres will then bear somewhat the same relation to the basalts that the diabases do to the dolerites. As thus defined, they are somewhat dull, black, dark brown, reddish, or green rocks, often amygdaloidal and showing their porphyritic minerals in an altered condition, the olivines especially being changed into serpentine or replaced by magnetite or even by hæmatite.[2]

Absarokite, Shoshonite, Banakite group.—Under this name Professor Iddings

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Cole, *Q. J. G. S.* xxxix. (1883), p. 444. Cole, *op. cit.* xliv. (1888), p. 300. P. F. Kendall, *Geol. Mag.* 1888, p. 555. M. F. Heddle, *Trans. Geol. Soc. Glasgow*, 1893, p. 80. Cohen, *Neues Jahrb.* 1876, p. 744; 1880 (ii.), p. 23 (Sandwich Islands).

[1] A. G., *Trans. Roy. Soc. Edin.* xxix. (1879), p. 437. Presidential Address, *Q. J. G. S.* (1892), p. 129, and 'Ancient Volcanoes of Britain,' i. p. 418, where the types of microscopic structure observed by Dr. Hatch and Professor Watts are enumerated.

[2] For some account of the use of the word melaphyre see Brongniart, 'Classification et Caractères minéralogiques des Roches homogènes et hétérogènes,' 1827, p. 106. Naumann, 'Lehrbuch der Geognosie,' i. p. 587. Zirkel, 'Petrographie,' ii. p. 847. Rosenbusch 'Mikroskop. Physiogr.' ii. p. 1044.

has described a series of rocks associated with the basalts and andesites of the Yellowstone National Park, having a basaltic aspect and occurring as lava-flows and dykes. They possess a considerable range of texture and composition, and for convenience are subdivided into three classes which graduate into each other. The first and most basic class (Absarokite) has a ground-mass varying from a dark glass through aphanitic forms to an almost phanerocrystalline light grey mass, and enclosing abundant phenocrysts of olivine and augite, but with none of felspar. The proportion of silica is from 46 to 52 per cent, of alumina 9 to 12, of magnesia 8 to 13, and a moderately high percentage of alkalies, the potash being generally higher than the soda. The second class (Shoshonite) is distinguished by the presence of phenocrysts of labradorite, augite and olivine, with silica 50 to 56 per cent, alumina 17 to 19·7, lime 4·3 to 8, magnesia 2·5 to 4·4, potash 3·4 to 4·4, soda 3 to 3·9. The rocks of the third class (Banakite), mostly found in dykes, are highly felspathic with a smaller amount of ferromagnesian minerals, chiefly biotite with subordinate augite. These contain 51 to 61 per cent of silica, 16·7 to 19·6 of alumina, 3·5 to 6 of lime, 1 to 4 of magnesia, 3·8 to 4·5 of soda, and 4·4 to 5·7 of potash.[1]

Nepheline-basalt, &c.—Zirkel proved that certain black heavy rocks, having externally the aspect of ordinary basalt, contain little or no felspar, the part of that mineral being taken in some by nepheline, in others by leucite. They are volcanic masses of late Tertiary age, but occur much more sparingly than the true basalts. When nepheline entirely replaces felspar the rock is known as Nepheline-basalt if it contains olivine, and Nephelinite when that mineral is absent. Nepheline-basalt is widely distributed on the continent of Europe. Thus it appears in the Eifel, the Odenwald, Hesse, Franconia, Saxony, Bohemia, France, the Pyrenees and Scania, yet it has never been detected in any part of the vast tracts of felspar-basalt that extend from the north of Ireland through the Western Isles and the Faroe Isles into Iceland and Greenland. Nephelinite is found in many of the districts where Nepheline-basalt occurs.

Nepheline-basanite is the name assigned to those varieties in which both felspar and nepheline occur, together with olivine; when the latter is absent the rock is called Nepheline-tephrite.[2] These rocks have a similar distribution to those mentioned in the foregoing paragraph. They are found also in the Canary Islands.

Mr. Washington has distinguished by the name of Kulaite an allied rock from Lydia in Asia Minor, containing perhaps 20 per cent of nepheline, besides anorthite, albite and orthoclase, together with diopside and olivine.[3]

A similar series of compounds to those just described occurs with leucite instead of nepheline as the felspathoid. Leucite-basalt contains no felspar, and has olivine as an essential constituent; when that mineral is absent the aggregate is called Leucitite. Again, when felspar is present besides the leucite, the rock is known as Leucite-basanite if it contains olivine, and Leucite-tephrite if it does not. These rocks have a general resemblance externally to felspar-basalt, with which they were at first confounded. They are found among the extinct volcanoes of the Eifel and Italy, and in the modern lavas of Vesuvius. Leucite-basalt occurs together with nepheline-basalt in various parts of the Continent, particularly the Eifel, Hesse, Erzgebirge and Bohemia. Leucitite has been noticed in the Eifel, but its chief European region is among the old volcanic tracts of Italy, especially Bracciano and Albano. It has been met with in Wyoming, and has there suggested the name of "Leucite Hills." Leucite-basanite has also been sparingly found in the Eifel, more abundantly in Bohemia, but most plentifully among the ancient and modern lavas of Italy, the modern

[1] J. P. Iddings, *Journ. Geol.* iii. (1895), p. 935.

[2] For a detailed account of Nepheline-tephrite see K. Hinterlechner, "Ueber Basaltgesteine aus Ostböhmen," *Jahrb. K. K. Geol. Reichsanst.* Vienna, 1900, pp. 469-526.

[3] *Journ. Geol.* viii. (1900), p. 610, and previous writings there cited.

lava-streams of Vesuvius being referable to this rock. Leucite-tephrite is met with at the Kaiserstuhl, in Northern Bohemia, and at Rocca Monfina and other volcanic districts of Italy.[1]

Melilite-Basalt.—In continuation of Zirkel's research, A. Stelzner showed that in some basalts the part of felspar and nepheline is played by melilite.[2] In outer appearance the rocks possessing this composition, and to which the name of Melilite-basalt has been given, cannot be distinguished from ordinary basalt. Under the microscope, the ground-mass appears to be mainly composed of transparent sections of melilite, either disposed without order, or ranged in fluxion lines round the large olivine and augite crystals; but it also contains chromite (?), microlitic augite, brown mica, abundant magnetite, with perowskite, apatite, and probably nepheline. (Swabian Alb, Bohemia, Saxon Switzerland, &c.)

A melilite-basalt from Alnö, on the coast of Westernorrland, Sweden, was described in 1882, by Mr. A. E. Törnebohm, as made up of melilite, mica, augite, olivine, apatite and magnetite. It occurs as a dyke, and was consequently separated from the effusive melilite-basalts by Rosenbusch and named Alnoite. Since that time other instances of a similar rock, likewise of intrusive character, have been met with in Finland, and in British North America.[3]

Analcite-basalt—A basalt-like rock in which the part of the felspar or felspathoid is taken by analcite. The ground is black and aphanitic, and through it are dispersed crystals of augite, olivine and magnetite. To some rocks of this character the name of Monchiquite (from Monchique in Southern Portugal) was given in 1890 by Rosenbusch. Since that time, mainly owing to the labours of Messrs. Lindgren, Kemp, Williams, Pirsson, and Whitman Cross in the United States, it has been ascertained that analcite plays a more important part as a primary rock constituent than had ever been supposed. Mr. Pirsson has proposed to institute a special division of igneous rocks as the analcite series. This he further subdivides into two groups—the Analcite-basalts or Monchiquites, containing olivine, and thus corresponding to the leucite-basalts; and the Analcitites or forms without olivine, corresponding to the nephelinites and leucitites ("Fourchites" of J. F. Williams).[4]

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[1] For some recent analyses of these Italian rocks see the series of papers by Mr. Washington, quoted *ante*, p. 228.

[2] *Neues Jahrb.* (Beilageband), 1883, pp. 369-439.

[3] Törnebohm, *Geol. Fören. Förhandl. Stockholm*, vi. (1882), p. 240; Rosenbusch, 'Massig. Gest.' p. 547; Ramsay and Nyholm, *Bull. Com. Geol. Finlande*, No. 1 (1895); Ferrier, 'Kamloops Sheet, British Columbia,' p. 40; F. D. Adams, On a Melilite-bearing Rock from near Montreal, *Amer. Journ. Sci.* xliii. (1892), p. 269.

[4] Rosenbusch, *Tschermak's Mitth.* xi. (1890), p. 445; Lindgren, *Proc. Californ. Acad. Sci.* 2nd ser. iii. 1890; J. F. Kemp, *Bull. U. S. G. S.* No. 107, 1893; J. F. Williams and J. F. Kemp, *Ann. Rep. Geol. Surv. Arkansas*, ii. (1890), p. 392; L. V. Pirsson, *Journ. Geol.* iv. (1896), p. 679; *20th Ann. Rep. U. S. G. S.* (1900), Part iii. p. 543; W. Cross, *Journ. Geol.* v. (1897), p. 684.

CHEMICAL COMPOSITION OF THE GABBRO, DOLERITE AND BASALT FAMILY.

| | I. | II. | III. | IV. | V. | VI. | VII. | VIII. | IX. | X. |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 56·20 | 48·91 | 52·81 | 48·25 | 51·68 | 48·76 | 40·32 | 50·24 | 33·89 | 45·59 |
| $Al_2O_3$ | 15·46 | 8·81 | 16·60 | 16·73 | 15·87 | 15·89 | 9·46 | 20·09 | 9·93 | 12·98 |
| $Fe_2O_3$ | 1·54 | 1·04 | 2·66 | 3·99 | 1·46 | 6·04 | 4·75 | 2·54 | 15·63 | 4·97 |
| FeO | 9·76 | 9·52 | 6·13 | 6·28 | 8·43 | 4·56 | 7·48 | 5·65 | ... | 4·70 |
| MgO | 1·83 | 15·19 | 6·12 | 5·77 | 7·84 | 5·98 | 18·12 | 3·65 | 16·14 | 8·36 |
| CaO | 5·39 | 14·69 | 10·14 | 8·32 | 11·08 | 8·15 | 10·55 | 7·83 | 15·19 | 11·09 |
| $Na_2O$ | 2·78 | 0·64 | 2·79 | 3·24 | 1·86 | 3·43 | 2·62 | 2·97 | 2·86 | 4·53 |
| $K_2O$ | 2·56 | 0·10 | 1·05 | 4·08 | 0·34 | 2·93 | 1·10 | 7·45 | ... | 1·04 |
| $H_2O$ | 0·75 | 0·59 | 0·92 | 1·72 | 0·31 | 1·88 | 1·82 | 0·36 | 2·90 | 3·91 |
| $Ti_2O$ | 2·25 | 0·37 | 0·84 | 0·89 | 0·72 | 1·65 | 2·66 | ... | 0·64 | 1·32 |
| $P_2O_5$ | 1·13 | trace | 0·23 | 0·68 | 0·12 | 0·60 | 0·68 | ... | 1·41 | 0·91 |
| $Cr_2O_3$ | ... | 0·15 | ... | .. | ... | ... | ... | ... | ... | ... |
| MnO | 0·13 | 0·16 | undet. | trace | 0·15 | 0·13 | 0·25 | trace | trace | 0·14 |
| NiO | ... | ... | ... | ... | ... | ... | 0·06 | ... | ... | ... |
| BaO | 0·17 | ... | 0·03 | 0·01 | ... | 0·17 | 0·06 | .. | ... | 0·13 |
| $ZrO_2$ | ... | ... | ... | ... | ... | ... | ... | ... | ... | 0·03 |
| SrO | trace | ... | trace | ... | ... | 0·06 | 0·03 | .. | ... | 0·12 |
| $Li_2O$ | none | trace | trace | ... | ... | .. | trace | ... | ... | ... |
| $CO_2$ | none | ... | ... | ... | ... | ... | ... | ... | 1·41 | ... |
| S | 0·07 | .. | ... | ... | ... | ... | 0·01 | .. | ... | ... |
| $SO_3$ | trace | ... | ... | 0·12 | ... | ... | 0·03 | ... | ... | ... |
| Cl | trace | ... | ... | 0·08 | . | ... | 0·05 | ... | . | 0·05 |
| F | trace | ... | ... | ... | ... | ... | 0·04 | ... | . | ... |
| | 100·02 | 100·17 | 100·32 | 100·16 | 99·86 | 100·23 | 100·09 | 100·78 | 100·00 | 99·87 |

I. Quartz-gabbro, 2 miles south-east of Walleska, Cherokee County, Georgia. Analysed by H. N. Stokes, *Bull. U. S. G. S.* No. 168 p. 55 : contains essentially plagioclase (near labradorite) and augite with accessory magnetite, ilmenite, apatite and zoisite, orthoclase sparingly present, quartz in vitreous masses (A. H. Brooks).

II. Olivine-gabbro, Orange Grove, Baltimore County, Maryland. Analysed by W. F. Hillebrand, *op. cit.* p. 44 : contains plagioclase, diallage, hypersthene, fresh olivine, magnetite and apatite, sometimes hornblende.

III. Dolerite with scarcely any olivine, Mount Ingalls, Plumas County, California. Analysed by W. F. Hillebrand, *op. cit.* p. 189.

IV. Dolerite, dyke near Valmont, Denver Basin, Colorado. Analysed by L. G. Eakins, *op. cit.* p. 140 : described by Whitman Cross as containing augite, plagioclase, olivine, orthoclase and biotite, with accessory magnetite and apatite.

V. Typical Diabase, Rocky Ridge, Maryland. Analysed by E. A. Schneider, *op. cit.* p. 50.

VI. Plagioclase-basalt, Saddle Mountain, Pikes Peak district, Colorado. Analysed by W. F. Hillebrand, *op. cit.* p. 145 : phenocrysts of augite and olivine in a ground mass of plagioclase, orthoclase, augite, magnetite, biotite and apatite (Whitman Cross, *Journ. Geol.* v. p. 684).

VII. Nepheline-basalt, Tom Munns Hill, Uvalde quadrangle, Texas. Analysed by W. F. Hillebrand, *op. cit.* p. 62 : contains olivine, augite, nepheline, magnetite and apatite ; specific gravity, 3·148 (Whitman Cross). In this analysis the $Al_2O_3$ includes some $Cr_2O_3$.

VIII. Leucite-tephrite, Monte Cavallo, Bolsena, Italy. Analysed by H. S. Washington, *Journ. Geol.* v. (1897), p. 370.

IX. Melilite-basalt, Hochbohl in the Swabian Alb. Analysed by T. Meyer, *Neues Jahrb.* ii., 1882 (Beilageb.), p. 398.

X. Analcite-basalt, Denver Basin, Colorado. Analysed by W. F. Hillebrand, *Bull. U. S. G. S.* No. 168, p. 146: contains phenocrysts of augite, olivine and analcime, also magnetite with subordinate amounts of alkali felspars, biotite and apatite (Whitman Cross, *Journ. Geol.* v. p. 684).

### ix. Limburgite Family.

Here may be placed a group of volcanic rocks of highly basic composition, distinguished by the absence of felspar or of any felspathoid substance. These and those of the next family are sometimes termed the "Ultrabasic series."

**Limburgite** (Magma-basalt)—a fine-grained to vitreous volcanic rock, composed of augite, olivine, magnetite or titaniferous iron, and apatite. The base is generally glassy and the proportion of silica in the rock is only about 42 per cent. The typical locality is Limburg, near the Kaiserstuhl in Baden, but the rock occurs also in middle Germany, Bohemia, Scania, Spain, and among the Carboniferous volcanic rocks of Central Scotland.

**Augitite** is the name given to another volcanic rock consisting essentially of augite and magnetite in a glassy base. The absence of olivine separates this rock from limburgite. Augitite is found less commonly than the last-named. It occurs in Northern Bohemia, the Cape Verd Islands, and in the Limerick Carboniferous volcanic district of Ireland.[1]

### x. Peridotite Family, including Serpentine.

The rocks here embraced stand at the extreme end of the basic igneous rocks, as the rhyolites and granites stand at the opposite end of the acid series. They contain no felspar, or at least an insignificant proportion of it, and consist of olivine, with augite, hornblende or mica, magnetic or titaniferous iron, chromite and other allied minerals of the spinel type. Their specific gravity ranges between 3·0 and 3·3. When quite fresh they have a holocrystalline structure, but they are generally more or less altered, and in their extreme condition of alteration form rocks known as Serpentines. They are for the most part intrusive in behaviour, and not infrequently form parts of larger less basic bodies. Those varieties in which olivine is the chief constituent are the true Peridotites, and are sometimes called by that name with the prefix of the predominant mineral, *e.g.* Hornblende-peridotite, Augite-peridotite, Enstatite-peridotite, &c. The following special names have also been given.

**Dunite** (Olivine-rock), named by F. von Hochstetter from the Dun Mountain, New Zealand, consists of a granitoid mixture of olivine with chromite or other spinelloid. Such a rock passes naturally by alteration into a serpentine.

**Picrite**[2] (Palæopicrite, Picrite-porphyry)—a rock rich in olivine, usually more or less serpentinised, with augite, magnetite, or ilmenite, brown biotite, hornblende, or apatite, and usually a little plagioclase; occurs as an eruptive rock among Palæozoic and younger formations; is closely related to the diabases, into which by the addition of plagioclase it naturally passes. When hornblende predominates over pyroxene the rock is called Hornblende-picrite; where the augite prevails it is Augite-picrite. In the same way there are Enstatite-picrite, Mica-picrite, and various other combinations.

**Eulysite**, a mixture of olivine with augite and garnet, which has been met with in schistose lenticular bands among the crystalline schists of Scandinavia.

**Wehrlite** (Diallage-olivine-rock)—a coarse-grained aggregate of olivine (making 40

[1] For notices of the Bohemian Limburgites and Augitites see the paper of K. Hinterlechner, *Jahrb. K. K. Geol. Reichsanst.* 1900, pp. 497, 509; for the Irish example, B. Hobson, *Geol. Mag.* 1892, p. 348.

[2] So named from πικρός, bitter, in allusion to the large proportion of bitter-earth (Magnesia)—a character shared by all the peridotites. Gümbel, 'Die Palaeolithischen Eruptivgesteine des Fichtelgebirges': Munich, 1874.

per cent of the rock), diallage, amphibole and much titaniferous iron; found in association with gabbro in Hungary.

**Harzburgite** (Enstatite-olivine-rock, Saxonite, Schillerfels) — serpentinised olivine with rhombic pyroxene, found near Harzburg, in East Slavonia, in the Monte Rosa district and in Maryland, supplies another illustration of the local and limited occurrence of peridotites, being found as layers or patches in such rocks as gabbro and norite (p. 232).

**Lherzolite**[1]—(so named from L'herz in the Ariège), a holocrystalline rock composed of olivine, enstatite and diopside, with a lesser proportion of a spinelloid, sometimes brown (chromite, picotite), sometimes green (pleonast), and iron ores.

**Cortlandtite** (Amphibole-olivine-rock) — so named from its occurrence in the "Cortlandt series" of eruptive rocks on the Hudson River, where it consists of a dark green fine-grained rock, with large hornblende prisms, fresh olivine, hypersthene, sometimes also diallage, biotite, apatite and hercynite. This rock passes over into the hornblende-picrites.

**Biotite-olivine-rock**, composed of olivine with biotite, has been observed as an integral part of the norite near Harzburg, where it probably occurs as one of the lenticular bands already referred to as characteristic of the gabbros.

**Ariegites**—under this name M. Lacroix has recently proposed to group the remarkable rocks which he has found in bands or veins of the lherzolites of the Pyrenees and Ariège. They are holocrystalline, granular aggregates of one or several pyroxenes (diopside, diallage, bronzite) and dark green spinell, sometimes with pyrope garnet, brown ferriferous hornblende, which sometimes entirely replaces the pyroxene and is then accompanied by biotite. These rocks sometimes contain a little olivine, but they are pyroxenolites rather than peridotites. They may be most conveniently noticed here in connection with the lherzolites, of which they form a subordinate part.[2]

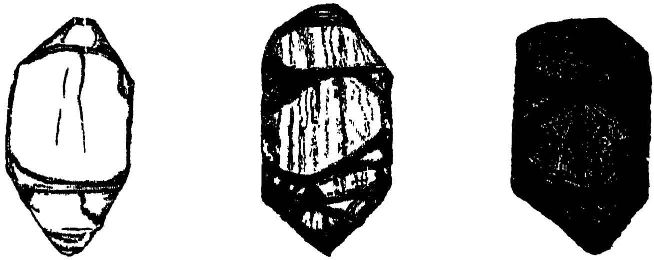
**Serpentine.**[3]—Under this name are included rocks which, whatever may have been their original character and composition, now consist mainly or wholly of serpentine. As already stated, olivine readily passes into the condition of serpentine, while the other minerals may remain nearly unaffected, as is admirably seen in some picrites. Most serpentine rocks originally consisted principally of olivine (see Figs. 32, 33). Diorite, gabbro, and other rocks, consisting largely of magnesian silicates, likewise pass into serpentine. If varieties due to different phases of alteration were judged worthy of separate designation, each member of the peridotites might of course have a conceivable or actual representative among the serpentines. But without attempting this minuteness of classification, we may with advantage treat by itself, as deserving special notice, the massive form of the mineral serpentine from whatsoever rock it may have originated.

[1] This rock, with its phenomena of contact, is the subject of a detailed mineralogical study by M. Lacroix, *Nouvelles Archiv. Muséum*, 3 ser. vi. p. 209. See also his notices in *Compt. rend.* cxv. (1892), pp. 974 and 976.

[2] Lacroix, *Compt. rend.* cxxv. (1895), p. 752, and cxxxii. 11th February 1901.

[3] See Tschermak, *Sitz. Akad. Wien*, lvi. July 1867; it was this author who first showed the derivation of serpentine from original olivine rocks; Bonney, *Q. J. G. S.* xxxiii. p. 884, xxxiv. p. 769; *Geol. Mag.* (2) vi. p. 362, vii. (1880), p. 538; (3) i. p. 406; Michel-Lévy, *B. S. G. F.* vi. 3rd ser. p. 156; Sterry Hunt, *Trans. Roy. Soc. Canada*, i. (1883); Dathe, *Neues Jahrb.* 1876, pp. 236, 337, where Garnet-serpentine and Bronzite-serpentine are described from the Saxon granulite region; J. S. Diller, *Bull. U. S. G. S.* No. 38 (1887); M. E. Wadsworth, 'Lithological Studies' (1884), p. 118; *Bull. Geol. Nat. Inst. Surv. Minnesota*, No. 2 (1887); J. W. Judd, *Q. J. G. S.* xli. (1885), p. 354; C. A. M'Mahon, *Proc. Geol. Assoc.* xi. No. 8 (1890). An account of the relations of a series of gabbros, peridotites and serpentines is given by H. W. Fairbanks, *Bull. Dept. Geol. Univ. California*, ii. (1896), pp. 50-85; G. Trabucco, 'Sulla posizione ad età delle Serpentine Terziarie dell' Appennino Settentrionale,' Florence, 1896.

Massive serpentine is a compact, or finely granular, faintly glimmering, or dull rock, easily cut or scratched, having a prevailing dirty-green colour, sometimes variously streaked or flecked with brown, yellow or red. It frequently contains other minerals besides serpentine. One of its commonest accompaniments is chrysotile or fibrous



A B C

Fig. 32.—Stages in the alteration of Olivine. A, the nearly fresh crystal; B, the alteration half completed; C, the crystal wholly serpentinised.

serpentine, which in veinings of a silky lustre often ramifies through the rock in all directions. Other common enclosures are bronzite, enstatite, magnetite, and chrome-spinels, besides traces of the original olivine, pyroxene, amphibole, mica, or felspar in the rocks which have been altered into serpentine.

As to its mode of origin, there can be no doubt that in most cases serpentine was originally an eruptive rock, as is clearly shown by its occurrence in dykes and irregular bosses. The frequent occurrence of recognisable olivine crystals, or of their still remaining contours, in the midst of the serpentine-matrix, affords good grounds for assigning an eruptive origin to many serpentines which have no distinctly eruptive external form (Fig. 33). The rock cannot, of course, have been ejected as the hydrous magnesian silicate serpentine; we must regard it as having been originally an eruptive olivine rock, or a highly hornblendic or micaceous diorite, or olivine-gabbro. In regions of crystalline schists beds of foliated serpentine are met with, more especially in connection with altered limestones (West of Ireland, Highlands of Scotland, Northern Apennines).[1] Some writers have contended that such serpentines are products of the alteration of dolomite, the magnesia having been taken up by silica, leaving the carbonate of lime behind as beds of limestone. Others have supposed the original rocks, from which the serpentines were derived, to have been a deposit from oceanic water, as has been suggested by Sterry Hunt in the case of those associated with crystalline schists.[2] Beds of serpentine intercalated with limestone might conceivably have been due to the elimination of magnesian silicates from sea-water by organic agency, like the glauconite now found filling the chambers of *foraminifera*, the cavities in corals, the canals in shells, sea-urchin spines and other organisms on the floor of the present

Fig. 33.—Microscopic Structure of Serpentine (20 diameters).

[1] The serpentines of Northern Italy are intercalated in the Upper, Middle, and Lower Eocene formations of that region. See the memoir of M. Trabucco, above cited.

[2] 'Chemical Essays,' p. 123.

sea.[1] Some excellent examples of the association of foliated serpentines are to be seen among the crystalline (Dalradian) schists of Banffshire. The serpentine occurs there in thick lenticular beds which, with a schistose crumpled structure, agree in dip with the surrounding rocks. They may have been deposits of contemporaneous origin with the limestones and schists among which they occur, and in association with which they have undergone the characteristic schistose puckering and crumpling. Sometimes they suggest a source from the alteration of highly basic volcanic tuffs. In other cases they may have been erupted peridotites, either flows or sills, which have acquired a schistose character from the same process of mechanical deformation that has played so large a part in producing the foliation of the crystalline schists.

CHEMICAL COMPOSITION OF SOME ULTRA-BASIC ROCKS.

| | I. | II. | III. | IV. | V. | VI. | VII. |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 42·78 | 46·13 | 40·11 | 44·64 | 47·09 | 40·77 | 40·50 |
| $Al_2O_3$ | 8·66 | 4·69 | 0·88 | 5·85 | 16·99 | 1·16 | 0·78 |
| $Fe_2O_3$ | ... | 0·73 | 1·20 | 2·85 | 1·62 | 3·56 | 4·01 |
| $FeO$ | 17·96 | 16·87 | 6·09 | 4·50 | 3·60 | 1·47 | 2·04 |
| $MgO$ | 10·06 | 25·17 | 48·58 | 38·76 | 19·92 | 39·37 | 37·43 |
| $CaO$ | 12·29 | 4·41 | ... | 2·47 | 9·20 | none | 0·39 |
| $Na_2O$ | 2·31 | 0·08 | ... | ... | 0·50 | 0·14 | 0·28 |
| $K_2O$ | 0·62 | trace | ... | ... | 0·25 | 0·10 | 0·16 |
| $H_2O$ | 3·96 | 1·38 | 2·74 | 0·30 loss | 0·83 loss | 12·97 | 13·75 |
| $Ti_2O$ | 0·28 | 0·73 | ... | ... | ... | none | ... |
| $P_2O_5$ | ... | 0·07 | ... | ... | ... | trace | trace |
| $Cr_2O_3$ | ... | 0·04 | 0·18 | 0·20 | ... | 0·28 | 0·41 |
| $MnO$ | 0·95 | trace | ... | ... | ... | 0·09 | 0·13 |
| $NiO$ | ... | 0·09 | ... | ... | ... | 0·17 | 0·11 |
| $BaO$ | ... | trace | ... | ... | ... | ... | ... |
| $Li_2O$ | ... | ... | ... | ... | ... | trace | ... |
| S | ... | 0·24 | ... | ... | ... | ... | ... |
| Chromite | ... | ... | 0·56 | ... | ... | ... | ... |
| | 99·87 | 100·63 | 100·34 | 99·57 | 100·00 | 100·08 | 99·99 |

I. Limburgite, Limburg, Kaiserstuhl. Analysed by Rosenbusch, *Neues Jahrb.* 1872, p. 54. Specific gravity, 2·831 : carbonates previously removed with acetic acid.

II. Hornblende-picrite, North Meadow Creek, Montana. Analysed by Eakins, *Bull. U. S. G. S.* No. 168, p. 114 : contains hornblende, abundant fresh olivine, grains of pleonaste and iron-oxides, with occasional hypersthene.

III. Dunite, Corundum Hill, North Carolina. Analysed by T. M. Chatard, *op. cit.* p. 54. Olivine-rock containing a little chromite, *Bull. U. S. G. S.* No. 42, p. 45.

IV. Lherzolite, L'herz. Analysis given by Lacroix, *Compt. rend.* 11th February 1901.

V. Ariegite, Etang de L'herz. Analysed by Lacroix, *ibid.* Contains diallage, bronzite and spinell.

VI. Serpentine from alteration of salite, Osburn's soapstone quarry, Blandford, Connecticut Valley, Massachusetts. Analysed by W. F. Hillebrand, *Bull. U. S. G. S.* No. 168, p. 28 ; described by B. K. Emerson, *Monog. U. S. G. S.* No. xxix.

VII. Serpentine, Mount Diablo, California. Analysed by W. H. Melville, *Bull. U. S. G. S.* No. 168, p. 215 : derived from the pyroxenite of a peridotite-pyroxenite dyke. Turner and Melvile, *Bull. Geol. Soc. Amer.* ii. pp. 383-414.

[1] According to Berthier, one of the glauconitic deposits in a Tertiary limestone is a true serpentine. See Sterry Hunt, 'Chem. Essays,' p. 303.

## III. Schistose (Metamorphic).

In this section is comprised a series of rocks most of which present a remarkable system of divisional planes that are not original but have been superinduced upon them. At the one end stand rocks which are unmistakably of sedimentary origin, for their original clastic structure and bedding can often be distinctly seen, and they also sometimes contain organic remains similar to those found in ordinary unaltered sedimentary strata. At the other end come coarsely crystalline masses, which in many respects resemble granite, and the original character of which is not obvious. An apparently unbroken gradation can be traced between these extremes, and the series was termed by Lyell "metamorphic" from the changed form in which its members are believed now to appear. In the earlier stages the change has taken the form of cleavage, as in ordinary slate. Even in slate, however, as already remarked (p. 171), a beginning may be detected in the development of crystalline particles, and the crystalline re-arrangement may be traced in constantly advancing progression until the whole mass has become crystalline, and forms what is known as a schist.

Fig. 84.—Profile of a piece of Gneiss, showing the lenticular character of its folia, natural size. (B. N. Peach.)

The Crystalline Schists, properly so called, constitute a well-defined series of rocks. They are mainly composed of silicates. Their structure is crystalline, but is distinguished from that of the Eruptive or Massive rocks by its more or less closely parallel layers or folia, consisting of

materials which have assumed a crystalline character along these layers. The folia may be composed of only one mineral, but usually consist of two or more, which occur either in distinct, often alternate laminæ, or intermingled in the same layer. This structure resembles that of the stratified rocks, but it is differentiated (1) by the crystalline and often granulitic (p. 130) structure of the minerals; (2) by a striking want of continuity in the folia, which thicken out and then die away, reappearing after an interval on the same or a different plane (Fig. 34); (3) by a peculiar and very characteristic welding of the folia into each other, the crystalline particles of one layer being so intermingled with those

Fig. 35.—View of a hand-specimen of contorted Mica-schist, two-thirds natural size. (B. N. Peach.)

of the layers above and below it that the whole tends to cohere as a tough, not easily fissile mass; (4) by a prevalent remarkable and eminently distinctive puckering or crumpling (with frequent minute faulting) of the folia, which becomes sometimes so fine as to be discernible only under the microscope[1] (Fig. 36), but is often present conspicuously in hand-specimens (Fig. 35), and can be traced in increasing dimensions,

[1] On the microscopic structure of the crystalline schists, see Zirkel, "Microscopical Petrography' (vol. vi. of King's 'Exploration of 40th Parallel'), 1876, p. 14, and his 'Lehrbuch,' iii. pp. 141-425; Allport, *Q. J. G. S.* xxxii. p. 407; Sorby, *op. cit.* xxxvi. p. 81; Lehmann's 'Untersuchungen über die Entstehung der Altkrystallinischen Schiefergesteine,' Bonn, 1884; and other memoirs cited in subsequent pages.

till it connects itself with gigantic curvatures of the strata, which embrace whole mountains. These characters are sufficient to indicate a great difference between schistose rocks and ordinary stratified formations, in which the strata lie in continuous flat, parallel, and more or less easily separable layers.

In some instances, indeed, the folia can be seen to coincide with original bedding, as where a band of quartzite or of conglomerate is intercalated between sheets of phyllite or mica-schist. In such cases, there cannot be any doubt that the rock, though now more or less reconstructed and crystalline, was originally mechanical sediment. Many clay-slates, phyllites, and mica-schists are obviously only altered marine clays, and some of them still retain their recognisable fossils. From such rocks, gradations can be followed into chiastolite-schist, mica-schist, and fine gneiss. Quartzites and quartz-schists often still retain the false-bedding of the original sandy sediment of which they are composed, and even sometimes show their lines of heavy minerals, as these were assorted in that sediment. The pebbly and conglomeratic bands associated with some schists afford convincing proof of their original clastic nature. Thus, while at the one end of the schistose series we find rocks in which an original sedimentary character remains unmistakable, at the other end, after many intermediate stages, we encounter thoroughly amorphous crystalline masses, that bear the closest resemblance to eruptive rocks into which they insensibly pass. In such instances, it may be confidently inferred that the amorphous structure is the original one, which has become schistose by subsequent deformation. (Book IV. Part VIII.) But just as the traces of original stratification are not always obliterated in the schists which have been formed by the alteration of sedimentary strata, so the banded arrangement of coarse gneisses, and other crystalline schists, may sometimes be an original segregation-structure, like that observable in sills and bosses of gabbro and other eruptive rocks (pp. 131, 232).

In the more thoroughly re-constructed and re-crystallised schists all trace of the original structures has generally been lost. The foliation is not coincident with bedding, nor with any structure of eruptive rocks, but has been determined by planes of cleavage or of shearing, or by the alignment assumed by minerals crystallising under the influence of intense pressure. Along these surfaces the crushed constituents have rearranged themselves, and new chemical and mineralogical combinations have been effected during the progress of the "metamorphism."

A rock possessing a crystalline arrangement into separate folia is in English termed a Schist.[1] This word, though employed as a general designation to describe the structure of all truly foliated rocks, is also made use of as a suffix to the names of the minerals of which some of the foliated rocks largely consist. Thus we have "mica-schist," "chlorite-schist," "hornblende-schist." If the mass loses its fissile tendency, owing to the felting together of the component mineral into a tough

[1] In French this term has no such definite signification, being applied both to schists and to shales. In German also the corresponding word 'schiefer' designates schists, but is likewise employed for non-crystalline shaly rocks; thonschiefer = clay-slate: schieferthon = shale.

coherent whole, the word rock is usually substituted for schist, as in "hornblende-rock," "actinolite-rock," and so on. The student must bear in mind that while the possession of a foliated structure is the distinctive character of the crystalline schists, it is not always present in every individual bed or mass associated with these rocks. Yet the non-schistose portions are so obviously integral parts of the schistose series that they cannot, without great violation of natural affinities, be separated from them. Hence in the following enumeration they are included as common accompaniments of the schists. Quartzite also may be placed in this subdivision, though in its typical condition it shows no schistose structure.

The origin of the crystalline schists has been the subject of long discussion among geologists. Werner held that, like other rocks of high antiquity, they were chemical precipitates from a universal ocean. Hutton and his followers maintained that they were mechanical aqueous sediments altered by subterranean heat. These two doctrines in various modifications are still maintained by opposite schools. In recent years much light has been thrown upon the origin of the schistose structure, which has been shown to be in many cases due to the mechanical crushing and chemical re-adjustment and re-crystallisation of the materials of both sedimentary and igneous rocks. This subject is discussed in a later part of this volume. (See Book IV. Part VIII.)

It is obvious that a wide series of rocks embracing variously altered forms of both sedimentary and igneous materials hardly admits of any simple system of classification. Regarding them from the point of view of the nature of the metamorphism they have undergone, geologists have sometimes grouped these rocks as resulting either from contact-metamorphism, that is, from the effects of the protrusion of igneous matter out of the earth's interior, or from regional metamorphism where the changes have been brought about by some widespread disturbance of the terrestrial crust. (Book IV. Part VIII.) But this arrangement, though of value in discussing questions of metamorphism, has the disadvantage of introducing theoretical considerations, and of placing in different groups rocks which undoubtedly present the same general petrographical characters. Avoiding all disputed questions as to modes of origin, I shall group the schists according to their mineral characters, beginning with those which are obviously only a further stage of the alteration of clay-slates, and ending with the gneisses, which bear a close affinity to granites.

**Argillites, Argillaceous Schists, Phyllites** (Phyllades, Thonschiefer).—The rocks included in this group may often be traced into the clay-slates described on p. 170. They were originally mechanical (argillaceous) sediments, and mark a further stage of metamorphism, wherein, besides mechanical deformation, there has been a more or less decided crystallisation of the materials, as is demonstrated by the increase in number and size of the "needles" of the slates, by the greater development of secondary mica, and by the appearance of such minerals as chiastolite, andalusite, staurolite, garnet, &c.[1] When a clay-slate becomes lustrous by the development of mica, it is known as

[1] See the interesting papers by Professor Renard on the Phyllades of the Ardennes and the garnetiferous and hornblendic rocks of Bastogne, *Bull. Mus. Roy. Belg.* i. (1882), iii. (1884), and the analyses by M. C. Klement, *op. cit.* v. (1889), p. 183. Compare T. Mellard

Phyllite—a term which may be regarded as embracing the intermediate group of rocks between normal clay-slates and true mica-schists. Many phyllites show original bedding, often well marked by colour-bands and by the alternation of sandy layers, while the rocks sometimes even enclose organic remains. They are of all ages, from pre-Cambrian up to Tertiary.

Chiastolite-slate (Schiste maclé), a clay-slate in which crystals of chiastolite have been developed, even sometimes side by side with still distinctly preserved graptolites or other organic remains[1] (Skiddaw, Aberdeenshire, Brittany, the Pyrenees, Saxony, Norway, Massachusetts, &c.). Staurolite-slate, a micaceous clay-slate with crystals of staurolite (Banffshire, Pyrenees). Ottrelite-slate, a clay-slate marked by minute, six-sided, greyish or blackish green lamellæ of ottrelite (Ardennes, where it is said to contain remains of trilobites, Bavaria, New England). Dipyre-slate is full of small crystals of dipyre. Sericite-phyllite is a name proposed by Lossen for those compact, greenish, reddish, or violet sericite-schists in which the naked eye can no longer distinguish the component minerals. Mica-phyllite (*phyllade gris feuilleté* of Dumont), a silky, usually very fissile slate, with minute scales of mica. German petrographers have distinguished by name some other varieties found more particularly in areas of contact-metamorphism around masses of granite, and characterised by different kinds of concretions, but to which no special English designations have been given. Knotenschiefer (Knotted schist) contains little knots or concretions of a dark green or brown, fine-granular, faintly glimmering substance, of a talcose or micaceous nature, imbedded in a finely laminated matrix of a talc-like or mica-like mineral.[2] These aggregations appear to be in many cases incipient stages in the formation of definite crystals of such minerals as andalusite. In Fruchtschiefer the concretions are like grains of corn; in Garbenschiefer, like caraway seeds; in Fleckschiefer, like flecks or spots. Some of these rocks might be included with the mica-schists, into varieties of which they pass. Round some of the eruptive diabase of the Harz, the clay-slates have been altered into various crystalline masses to which names have been attached. Thus Spilosite is a greenish, schistose rock, composed of finely granular or compact felspathic material, with small chlorite concretions or scales. Desmosite is a schistose mass in which similar materials are disposed in more distinct alternations.[3] Hornfels, another result of contact-metamorphism, is referred to on p. 251.

**Quartz-schist**[4] (Schistose quartzite), an aggregate of granular (or granulitic) quartz with a sufficient development of fine folia of mica to impart a more or less definitely schistose structure to the rock. The disappearance of the mica gives quartzite, and the greater prominence of this mineral affords gradations into mica-schist. Such gradations are quite analogous to those among recent sedimentary materials from pure sand, through muddy sand, and sandy mud, into mud or clay, and between sandstones and shales. The Highlands of Scotland, for instance, embrace large tracts of quartz-schists—rocks which are not properly either mica-schist or ordinary quartzite. They consist of granular (granulitised) quartz, with fine parallel laminæ of mica, and are

Reade and P. Holland, "The Phyllades of the Ardennes compared with the Slates of North Wales," *Proc. Liverpool Geol. Soc.* 1897-98, p. 274, and 1899-1900, p. 463.

[1] A good illustration of this association is figured by Kjerulf in his 'Geologie des Südlichen und Mittleren Norwegen,' Plate xiv. Fig. 246. See also Brögger's memoir on Upper Silurian fossils among the crystalline rocks of Bergen: Christiania, 1882. A similar association occurs in the graptolite-shales next the granite of Galloway, Scotland.

[2] A. von Lasaulx, *Neues Jahrb.* 1872, p. 840. K. A. Lossen, *Z. D. G. G.* 1867, p. 585 (where a detailed description of the Taunus phyllites will be found), 1872, p. 757.

[3] Other names are *Bandschiefer*, *Contactschiefer*, &c. See K. A. Lossen, *Z. D. G. G.* xix. (1867), p. 509; xxi. p. 291; xxiv. p. 701; Kayser, *op. cit.* xxii. p. 103.

[4] J. Macculloch, *Trans. Geol. Soc.* 1st ser. ii. (1814), p. 450; iv. (1817), p. 264; 2nd ser. i. (1819), p. 58. Lossen, *Z. D. G. G.* xix. (1867), pp. 615-634.

capable of being split into thick or thin flagstones. Interstratified pebbly varieties occur.

Itacolumite—a schistose quartzite, in which the quartz-granules are separated by fine scales of mica, talc, chlorite, and sericite. Occasionally these pliable scales are so arranged as to give a certain flexibility to the stone (flexible sandstone). This rock occurs in the south-eastern states of North America; also in Brazil, as the matrix in which diamonds are found.

Siliceous schist (Lydian-stone, Lydite, Kieselschiefer) has already been described (p. 167) among the stratified rocks; but it also occurs among the crystalline schists, sometimes as the result of the pulverisation of quartzose rocks (Mylonite).

**Quartzite** (Quartz-rock), though not properly a schistose rock, may be most conveniently considered here, as it is so constant an accompaniment of the schists, and, like them, can often be directly traced to the alteration of former sedimentary formations. It is a bedded, granular to compact mass of quartz, generally white, sometimes yellow or red, with a characteristic lustrous fracture, occasionally pebbly, and even accompanied by conglomerates or boulder-beds. It occurs in association with schists, sometimes in continuous masses hundreds of feet thick. In Scotland it forms ranges of mountains, and in the north-west Highlands is crowded with annelide burrows and accompanied by beds of limestone which contain Cambrian fossils.[1]

Fig. 36.—Contorted Micaceous-schist, as seen under the microscope with a magnifying power of 50 diameters.

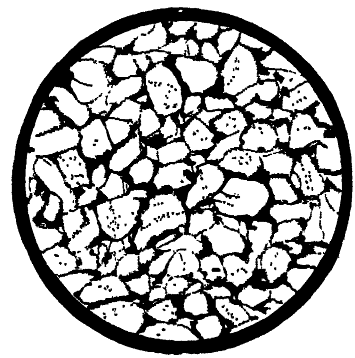


Fig. 37.—Microscopic Structure of Quartzite. (Magnified 20 diameters.)

Even to the naked eye, the finely granular or arenaceous structure of quartzite is distinctly visible. Microscopic examination shows this structure still more clearly, and leaves no doubt that the rock originally consisted of a tolerably pure quartz-sand (Fig. 37). More or less distinct evidence of crushing and deformation of the grains may often be observed, likewise proof of the transfusion of a siliceous cement among the particles. This cement was probably produced by the solvent action of heated water upon the quartz grains, which seem to shade off into each other, or into the intervening silica. It is owing, no doubt, to the purely siliceous character of the grains that the blending of these with the surrounding cement is so intimate as often to give the rock an almost flinty homogeneous texture. That quartzite, as here described, is an original sedimentary rock, and not a chemical deposit, is shown not only by its granular texture, but by the exact resemblance of all its leading features to ordinary sandstone—false-bedding, alternation of coarser and finer layers, accumulation of heavy minerals, worm-burrows,

[1] See the sections on the pre-Cambrian and Cambrian systems, Book VI. Parts I. and II. Sect. i. On the metamorphic quartzose rocks of Morbihan, France, see Barrois, *Ann. Soc. Géol. Nord.* xi. (1884). Compare Sollas, *Sci. Proc. Roy. Dublin Soc.* vii. (1892), p. 169.

and fucoid-casts. The lustrous fracture that distinguishes this rock from sandstone is due to the exceedingly firm cohesion of the component grains, which break across rather than separate, and to the consequent production of innumerable minute clear vitreous surfaces of quartz. A sandstone, on the other hand, has its grains so loosely coherent that when the rock is broken the fracture passes between them, and the new surface obtained presents innumerable dull rounded grains.

Besides occurring in alternation with schists, quartzite is also met with locally as an altered form of sandstone, which when traversed by igneous dykes is indurated for a distance of a few inches or feet from the intrusive mass. These local productions of quartzite show the characteristic lustrous fracture, and have not yet been distinguished by the microscope from the quartz-rock of wide metamorphic regions. There is still another condition under which this rock, or one of analogous structure, may be seen. Highly silicated bands, having a lustrous aspect, fine grain, and great hardness, occur among unaltered shales and other strata of Palæozoic and even of Tertiary age. In such cases the supposition of any general metamorphism being inadmissible, we may infer either that these quartzose bands have been indurated, for example, by the passage through them of silicated water, or that they are an original formation.

**Schistose Conglomerate Rocks.**—In some regions of schists, not only bands of quartzite occur, representing former sandstones, but also pebbly or conglomeratic bands, in which pebbles of quartz and other materials from less than an inch to more than a foot in diameter (boulder beds) are imbedded in a foliated matrix, which may be phyllite, mica-schist, gneiss, quartzite, &c.[1] Examples of this kind are found in the pass of the Tête Noire between Martigny and Chamouni, in the Saxon granulite region, in the Bergen region of Norway, in the north-west of France, in north-west Ireland, in the islands of Arran, Islay and Garvelloch, in Perthshire and in other parts of the central Highlands of Scotland. The pebbles are not to be distinguished from the water-worn blocks of ordinary conglomerates; but the original matrix which encloses them has been so altered as to acquire a micaceous foliated structure, and to wrap the pebbles round as with a kind of glaze. These facts, like those already referred to in the structure of quartzite and argillaceous and quartz-schist, are of considerable value in regard to the theory of the origin of some crystalline schists. Crush-conglomerates (p. 164) may also become schistose.

**Graphite-schist** is a name given to schistose bands which not improbably represent what once were carbonaceous shales but are now phyllites or mica-schists, with a black colour from the graphite with which they are filled. They have been met with in many regions of crystalline schists, and can sometimes, as in the Scottish Highlands, be followed for long distances.[2]

**Crystalline Limestone.**—Further evidence of the sedimentary origin of some crystalline schists is supplied by the occurrence of bands of limestone, which were doubtless originally deposits of calcareous sediment. They now always present a more or less distinctive crystalline structure (marmarosis). When purest they form white statuary Marble (p. 192), but the presence of original impurities has given rise to the production of a large number of included minerals.[3] Popular names have been given to the more marked

[1] Professor Wichmann describes some curious examples of serpentine conglomerates. See his paper in 'Beiträge zur Geologie Ost-Asiens und Australiens,' ii. pp. 35, 111. On the conglomerate-schists of Saxony, see A. Sauer, 'Geol. Specialkarte Sachsen,' Sect. "Elterlein"; also Lehmann's 'Altkryst. Schiefergesteine,' p. 124. Reusch, 'Silurfossiler og Pressede Konglomerater,' Christiania, 1882. Barrois, *Ann. Soc. Géol. Nord.* xi. 1884. A coarse conglomerate or "boulder-bed" forms a persistent band at the base of the quartzite series of the central and south-western Highlands of Scotland.

[2] Dr. Kotô has described a spotted graphite schist as attaining a considerable development among the crystalline schists of Chichibu in the main island of Japan, *Journ. Coll. Sci. Univ. Japan*, vol. ii. part ii. (1888), p. 96.

[3] See an alphabetical list of these minerals in Zirkel's 'Lehrbuch,' iii. p. 448.

varieties of marble that are available for ornamental purposes, these names being usually taken from the places whence the stones were first obtained, or from their colour or markings.[1] Among the terms of more geological significance the following may be noted: Cipollino—a marble showing bands (often plicated) of different shades of green, in which the calcite is interleaved with scales and folia of mica and talc, with sometimes other minerals. Ophicalcite—a fine-grained rock in which the calcite is mingled with green serpentine. Under the microscope the serpentine grains sometimes reveal a central core of still recognisable olivine.[2]

**Hornfels.**—Some impure limestones, dolomites and calcareous or dolomitic shales have by contact-alteration been converted into compact, close-grained rocks, in which the lime has been united to silicic acid, producing various lime-silicates (wollastonite scapolite, &c.). Such metamorphosed materials are known as Hornfels or lime-silicate-rocks (Kalksilicathornfels).

**Augite-schist**—a fine-grained schistose aggregate of pale or dark-green augite, with sometimes quartz, plagioclase, magnetite, or chlorite; found rarely among the crystalline schists. From the schistose rocks of the Taunus, Lossen described some interesting varieties under the name of Augite-schist (Augitschiefer). They are green, compact, sometimes soft and yielding to the finger-nail, usually distinctly schistose, and interbedded with the gneisses and schists. They are composed of a fine dull diabase-like ground-mass, through which are dispersed crystals of augite, 1 to 2 mm. in length, which in the typical varieties are the only components distinctly recognisable by the naked eye.[3]

**Augite-rock**[4]—a granular aggregate of augite (with tourmaline, sphene, scapolite, &c.), found in beds in the Laurentian limestone of Canada. Malacolite-rock is a pale granular to compact, or even fibrous aggregate of malacolite, found in beds in crystalline limestone (Riesengebirge).

**Greenstone-schist, Diabase-schist, Gabbro-schist.**—The suggestion made many years ago by J. Beete Jukes[5] that the bands of dark hornblendic material intercalated among the crystalline schists might represent former sheets of lava or tuff, which have been metamorphosed together with the sedimentary strata among which they were intercalated, has been amply confirmed by subsequent observation. The connection of some schists with original masses of diorite, gabbro and diabase was pointed out by Lehmann,[6] and his observations have been verified by later researches in many different parts of the world. It is now recognised that masses of eruptive rock, whether intrusive or contemporaneously interstratified as superfical lavas or tuffs, have sometimes been afterwards subjected to severe crushing under great pressure, and have thereby acquired a more or less distinctly foliated structure, without entirely losing all trace of their original character. Solid "eyes" or lenticular lumps are left between the material which has been crushed down and has re-crystallised as schist (Figs. 265, 266). Names are given to such schists to

[1] An exhaustive account of marbles will be found in 'History and Uses of Limestones and Marbles,' by S. M. Burnham, Boston, 1883, pp. xv., 392, with forty-eight chromolithographs of the stones.

[2] Zirkel, *Neues Jahrb.* 1870, p. 828. For accounts of a region of cipollinos and ophicalcites, see G. P. Merrill, *Amer. Journ. Sci.* March 1889, p. 189; also J. F. Kemp. *Bull. Geol. Soc. Amer.* vi. (1895), pp. 241-262.

[3] Lossen, *Z. D. G. G.* xix. (1867), p. 558.

[4] This term was applied by Macculloch to some of the Tertiary gabbros of the west of Scotland. It has also been given to some varieties of gabbro (p. 232).

[5] 'Students' Manual of Geology,' 2nd edit. (1862), pp. 169, 172.

[6] 'Untersuch. Entst. Altkrystall. Schief.' See also Gümbel, 'Die Paläolitischen Eruptivgesteine des Fichtelgebirges,' Munich, 1874, p. 9. Teall, *Q. J. G. S.* xli. (1883), p. 133; 'British Petrography,' p. 198. Hatch, *Mem. Geol. Survey*, "Explanation of Sheets 138, 139, Ireland," p. 49. Hyland, *Mem. Geol. Survey*, "Explanations of North-west Donegal, and of South-west Donegal," Petrographical Appendices. G. H. Williams, *Bull. U.S. G. S.* No. 62, 1890. This subject is further noticed in Book IV, Part VIII. Sect. ii.

express both their original and metamorphic character. Under the designation of Greenstone-schists the late G. H. Williams described a remarkable series of transformations of the basic eruptive rocks of the Menominee and Marquette regions of Michigan. Originally those rocks included olivine-gabbros, ordinary gabbros, diabase (the most frequent type), diabase-porphyry, melaphyre and diorite, but by a complex process of compression, faulting and crushing they have been transformed into various forms of schist.[1] In the Taunus a series of diabase-schists has been described by L. Milch.[2] Gabbro-schist is a granular to schistose aggregate of plagioclase and diallage which occurs in lenticular bands among the amphibolites and granulites of the crystalline schists. The diallage may appear in conspicuous crystals, and is sometimes associated with abundant olivine, as in ordinary gabbro (p. 231).[3]

**Amphibolites**— a name applied to a group of rocks, composed mainly of hornblende, sometimes schistose, sometimes massive. Besides the hornblende, numerous other minerals, such as are common among the schists, likewise occur,—orthoclase, plagioclase, quartz, augite and varieties, garnet, zoisite, mica, rutile, &c. Where the rock is schistose, it becomes an Amphibolite-schist or Hornblende-schist; or if the hornblende takes the form of actinolite, Actinolite-schist. Glaucophane-schist[4] —a bluish-grey or black rock, in which the soda-amphibole occurs in the form of the beautiful mineral glaucophane, is of somewhat rare occurrence. It is met with in Anglesey, the Southern Alps, Greece, Corsica, Celebes, Japan, California and Oregon. From the Greek island of Syra, where this form of schist has long been known, Mr. Washington has recently described the following varieties: Epidote-glaucophane-schist, Mica-glaucophane-schist; Quartz-glaucophane-schist; he notes also a Garnet-glaucophane-schist and a Zoisite-glaucophane schist from California. Actinolite-magnetite-schist occurs in the Mesabé Iron Range, north-eastern Minnesota.[5] Where an amphibolite is not schistose, it used to be termed *hornblende-rock*. Nephrite (Jade) is a compact, extremely finely fibrous variety. The presence of other minerals in noticeable quantity may furnish names for other varieties. Thus, where plagioclase (and some orthoclase) occurs, the rock becomes a Felspar-amphibolite, Dioritic amphibolite, or Diorite-schist.[6] Amphibolites occur as bands associated with gneiss and other members of the series of crystalline schists. They probably in most cases represent original sheets of basic igneous rock. Various types of amphibolite have been met with abundantly by the officers of the Geological Survey in the Highlands of Scotland and in Ireland, where what were doubtless originally pyroxenic masses erupted prior to the metamorphism of the region, have had their augite changed by paramorphism into hornblende, and have partially assumed a foliated structure, passing into Epidiorite (p. 224), Epidiorite-schist, amphibolite-schist, and even serpentine.

**Eclogite**, one of the most beautiful members of the crystalline-schist series, is a granular aggregate of grass-green omphacite (pyroxene) and red garnet, through which are frequently dispersed hornblende, quartz, kyanite, zoisite or white mica. It occurs

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1 *Bull. U. S. G. S.* No. 62 (1890).

2 *Z. D. G. G.* xli. (1889), p. 394.

3 Rocks of this character occur in the Saxon "Granulitgebirge," and also in Lower Austria. F. Becke, *Tschermak's Min. Mitth.* iv. p. 352. J. Lehmann's 'Untersuch. Entstehung Altkryst. Schiefer,' p. 190. C. W. Hall, "Gabbro-schists of S.W. Minnesota," *B. U. S. G. S.* No. 157 (1899).

4 On glaucophane-rocks, see H. Rosenbusch, 'Elemente der Gesteinslehre,' p. 521; *Sitzb. Akad. Wiss. Berlin*, xlv. (1898), p. 706. H. S. Washington, "A Chemical Study of the Glaucophane-schists," *Amer. Journ. Sci.* xi. (1901), pp. 35-59; Bonney, *Mineralog. Mag.* vii. p. 1, and viii. p. 151. A. Wichmann, *Neues Jahrb.* (1893), ii. p. 176.

5 W. S. Bayley, *Amer. Journ. Sci.* xlvi. (1893), p. 176.

6 See F. Becke, *Tschermak's Min. Mitth.* iv. p. 238. This author likewise distinguishes *diallage-amphibolite, garnet-amphibolite, salite-amphibolite, zoisite-amphibolite.*

in bands in Archæan gneiss and mica-schist.[1] To those varieties where the kyanite becomes predominant, the name of Kyanite-rock has been given. Garnet-rock is a crystalline-granular rock composed mainly of garnet, with hornblende and magnetite; by the diminution of the garnet it passes into an amphibolite. Kinzigite—a crystalline schistose rock, composed of plagioclase, garnet, and black mica, found in the Black Forest (Kinsig) and the Odenwald. In the island of Syra, among the various glaucophane-schists above referred to, a beautiful Glaucophane-eclogite occurs composed of large grains of green omphacite, red garnet, small prisms of blue glaucophane, with mica, quartz, rutile, and other minerals.

**Epidosite** (Quartz-epidote-rock, Pistacite-rock)—an aggregate of bright green epidote with some quartz, occurs with chlorite-schists (Canada), with granite and serpentine (Elba), and with syenite. Epidote-schist, a schistose greenish rock, with silvery lustre on the foliation surfaces, composed of epidote, sericite, magnetite, quartz, calcite, plagioclase, and specular iron.[2]

**Chlorite-schist** (Ripidolite-schist, Clinochlore-schist)—a scaly or granular schistose aggregate of some chloritic mineral (perhaps in most cases clinochlore), usually with quartz and often with felspar, talc, mica, epidote or magnetite, the last-named mineral frequently appearing in beautifully perfect disseminated octohedra. Occurs with gneiss and other schists in evenly bedded masses.

**Talc-schist**—a schistose aggregate of scaly talc, often with quartz, felspar, and other minerals; having an unctuous feel, and white or greenish colour. Occurs somewhat rarely in beds associated with mica-schists and clay-slate, and frequently contains magnetite, chlorite, mica, kyanite, and other minerals, including carbonates. A massive variety, composed of a finely felted aggregate of scales of talc, or chlorite, is called Potstone (Topfstein). Many rocks with a soapy or unctuous feel have been classed as talc-schist, which contain no talc, but a variety of mica (sericite-schist, &c.). Talc-schist, though not specially abundant, occurs in considerable mass in the Alps (Mont Blanc, Monte Rosa, Carinthia, &c.), and is found also among the Apennine and Ural mountains.

**Peridotites** of the Crystalline Schists.[3] Rocks of which olivine forms a main constituent occur as subordinate bands or irregular masses associated with gneisses and other schistose rocks. They were probably eruptive masses, contemporaneous with or subsequent to the surrounding gneisses and schists. The olivine is commonly associated with some pyroxenic mineral, hornblende, garnet, &c. The following varieties have received special names,—Garnet-olivine rock, Bronzite-olivine rock, Amphibole-olivine rock. Some of the rocks mentioned at pp. 240-243 may also be included here. Dunite, for example, which occurs in apparently eruptive form at Dun Mountain, near Nelson, New Zealand, is found in North Carolina in beds with laminated structure intercalated in hornblende-gneiss. Eulysite lies in lenticular layers in the Swedish gneiss. Many of these rocks have undergone much crushing and deformation, and pass into foliated forms of Serpentine, which must thus be reckoned as one of the schistose as well as one of the eruptive series. The remarkable schistose serpentines interbedded among phyllites, mica-schists, and limestones in Banffshire have been already referred to (p. 243).

**Hälleflinta**—an exceedingly compact, hornstone-like, felsitic, grey, yellowish, greenish, reddish, brownish, or black rock, composed of an intimate mixture of microscopic particles of felspar and quartz, with fine scales of mica and chlorite. It breaks

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[1] See A. Lacroix on the Eclogites of the Lower Loire, *Bull. Soc. Sci. Nat. de l'Ouest de la France*, Nantes, 1891.

[2] See Wichmann on Rocks of Timor, 'Beiträge zur Geologie Ost-Asiens und Australiens,' II. Part ii. p. 97, Leyden, 1884.

[3] See Tschermak, *Sitzb. Akad. Wissen.*, Vienna, lvi. (1867). F. Becke, *Tschermak's Min. Mitth.* iv. (1882), p. 322. E. Dathe, *Neues Jahrb.* 1876, pp. 255-337.

with a splintery or conchoidal fracture, presents under the microscope a finely crystalline structure, occasionally with nests of quartz, and is only fusible in fine splinters before the blow-pipe. Some of the rocks to which this name has been applied are probably felsitic lavas; others, though externally presenting a resemblance to felsite, occur in beds intimately associated with foliated rocks (Norway), and may be metamorphic products (perhaps altered fine sediments) due to the same series of changes that gave rise to the crystalline schists among which they lie.[1]

**Adinole** (Adinole-schist)—a rock externally resembling the last, but distinguished from it by its greater fusibility. It is an intimate mixture of quartz and albite, containing about 10 per cent of soda. It is a product of alteration, being found among the altered Carboniferous shales around the eruptive diabases of the Harz, in the altered Devonian rocks of the Taunus, and in the altered Cambrian rocks of South Wales.[2]

**Porphyroid**—a name variously applied (*ante*, p. 130), perhaps best reserved for rocks composed of a felsite-like ground-mass which has assumed a more or less schistose structure from the development of micaceous scales, and which contains porphyritically scattered crystals of felspar and quartz. The felspar is either orthoclase or albite, and may be obtained in tolerably perfect crystals. The quartz occasionally presents doubly terminated pyramids. The micaceous mineral may be paragonite or sericite. Porphyroid occurs in circumstances which indicate considerable mechanical deformation, as among the schistose rocks of Saxony,[3] in the Palæozoic area of the Ardennes,[4] as well as in Westphalia and other parts of Europe.[5] Most porphyroids are probably sheared forms of quartz-porphyry, or similar rocks, the fissile structure and the micaceous films being precisely such as would be produced by the crushing and partial re-crystallisation of these rocks. In some cases the original materials may have been volcanic tuff.

**Tourmaline-schist** (Schorl-schist, schorl-rock), a blackish, finely granular, quartzose rock with abundant granules and needles of black tourmaline (schorl), which occurs as one of the products of contact-metamorphism in the neighbourhood of some granites (Cornwall).

**Mica-schist** (Mica-slate, Glimmerschiefer), a schistose aggregate of quartz and mica, the relative proportions of the two minerals varying widely even in the same mass of rock. Each is arranged in lenticular wavy laminæ. The quartz shows great inconstancy in the number and thickness of its folia. It often presents a granular character, like that of quartz-rock, or passes into granulite. The mica lies in thin plates, sometimes so dovetailed into each other as to form long continuous irregular crumpled folia, separating the quartz layers, and often in the form of thin spangles and membranes running in the quartz (Figs. 35 and 36). As the rock splits open along its micaceous folia, the quartz may not be readily seen save in a cross fracture.

The mica in typical mica-schist is generally a white variety; but it is sometimes replaced by a dark species. In many lustrous, unctuous schists which are now found to have a wide extent, the silvery foliated mineral is ascertained to be a mica (sericite, margarodite, damourite, &c.), and not talc, as was once supposed. These were named by Dana hydro-mica-schists. Among the accessory minerals, garnet (specially characteristic), schorl, felspar, hornblende, kyanite, staurolite, chlorite, and talc may be mentioned. Mica-schist readily passes into other members of the schistose family. By addition of felspar, it merges into gneiss. By loss of quartz and increase of chlorite,

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1 For analyses see H. Santesson, 'Kemiska Bergsartanalyser,' 8vo, Stockholm, 1877; and for details as to the Swedish rocks, O. Nordenskjöld, *Geol. Fören. Stockholm*, xviii. (1895), pp. 653-682.

2 Lossen, *Z. D. G. G.* xix. (1867), p. 573. See also *Q. J. G. S.* xxxix. (1883), pp. 302, 320; Rosenbusch, 'Mikrosk. Physiog.'; F. Posepny, *Tschermak's Min. Mitth.* x. 175.

3 Rothpletz, *Geol. Survey Saxony*, "Explanation of Section Rochlitz."

4 De la Vallée Poussin and Renard, *Mém. Couronnées Acad. Roy. Belg.* 1876, p. 85.

5 Lossen, *Sitz. Gesellsch. Naturf. Freunde*, 1883, No. 9.

it passes into chlorite-schist, and by the loss of mica, into quartz-schist and quartzite. By failure of quartz and diminution of mica, with an increasing admixture of calcite, it may shade into calc-mica-schist (see below), and even into marble. Mica-schist varies in colour mainly according to the hue of its mica.

Mr. Sorby has stated that thin slices of some mica-schists, when examined under the microscope, show traces of original grains of quartz-sand and other sedimentary particles of which the rock at first consisted. He has also found indications of what he supposes to have been current-bedding or ripple-drift, like that seen in many fine sedimentary deposits, and he concludes that mica-schist is a crystalline metamorphosed sedimentary rock.[1] In many, if not in most cases, however, the foliation does not correspond with original bedding, but with structural planes (cleavage, faulting) superinduced by pressure, tension, or otherwise, upon rocks which may not always have been of sedimentary origin.

Among the varieties of mica-schist may be mentioned Sericite-schist (which may be also included among the phyllites), composed of an aggregate of fine folia of the silky variety of mica called sericite, in a compact honestone-like quartz; Paragonite-schist, where the mica is the hydrous soda variety, paragonite; Gneiss-mica-schist, containing dispersed kernels of orthoclase. Other varieties have been named Sillimanite-mica-schist, Epidote-mica-schist, Chloritoid-mica-schist, Graphite-mica-schist. Some of these rocks contain little or no quartz, the place of which is taken by felspar. Calc-mica-schist is a schistose calcareous rock, which in many, if not in all cases, was originally a limestone with more or less muddy impurity. The carbonate of lime has assumed a granular-crystalline form, while the aluminous silicates have re-crystallised as fine scales of white mica. Tremolite, zoisite, and other minerals are not infrequent in this rock.

Normal mica-schist, together with other schistose rocks, forms extensive regions in Norway, Scotland, the Alps, and other parts of Europe, and vast tracts of the "Archæan" regions of North America. Some of its varieties are also found encircling granite masses (Scotland, Ireland, &c.) as a zone or aureole of contact-metamorphism from a few yards to a mile or so broad, which shades away into unaltered greywacke or slate outside. In these cases, mica-schist is unquestionably a metamorphosed condition of ordinary sedimentary strata, the change being connected with the extravasation of granite. (Book IV. Part VIII.)

Though the possession of a fissile structure, showing abundant divisional surfaces covered with glistening mica, is characteristic of mica-schist, we must distinguish between this structure and that of many micaceous sandstones which can be split into thin seams, each splendent with the sheen of its mica-flakes. A little examination will show that in the latter case the mica exists merely in the form of detached worn (clastic) scales, which, though lying on the same general plane, are not welded into each other as in a schist; also that the quartz does not exist in folia but in rounded separate grains. In mica-schist, on the other hand, the minerals have crystallised *in situ*.

**Gneiss.**—This name, formerly restricted to a schistose aggregate of orthoclase (often microcline or a plagioclastic felspar, either separate or crystallised together), quartz, and mica, is now commonly employed in a wider sense to denote the coarser schists which so often present granitoid characters.[2] Many gneisses, indeed, differ from granite chiefly

[1] *Q. J. G. S.* (1863), p. 401, and his address in vol. xxxvi. (1880), p. 85. The apparent current-bedding of many granulitic and other metamorphic rocks is certainly deceptive, and must be due to planes of shearing or slipping in the mechanical movements which produced the metamorphism.

[2] See Kalkowsky's 'Gneissformation des Eulengebirges,' Leipzig, 1878; Lehmann's 'Altkrystallinische Schiefergesteine,' 1884; F. Becke, *Tschermak's Min. Mitth.* 1882, p. 194; E. Weber, *op. cit.* 1884, p. 1, and *postea*, Book IV. Part VIII. § ii., and the account

in the foliated arrangement of the minerals. Others again are of intermediate composition, while some are decidedly basic. This wide range of chemical constitution is what might be expected if these rocks have to any large extent been produced by the dynamic and thermal metamorphism of eruptive masses of diverse composition. In minute structure the gneisses present many points of affinity with the massive rocks. Thus the quartz sometimes contains abundant liquid and gas inclusions, in which carbon-dioxide has been detected (p. 142). The relative proportions of the minerals, and the manner in which they are grouped with each other, in many respects recall the eruptive rocks, but are still more varied. As a rule, the folia are coarser, and the schistose character less perfect than in mica-schist. Sometimes the quartz lies in tolerably pure bands, a foot or even more in thickness, with plates of mica scattered through it. These quartz layers may be replaced by a crystalline mixture of quartz and felspar, or the felspar will take the form of independent lenticular folia, while the laminæ of mica which lie so abundantly in the rock give it its fissile structure. The felspar of many gneisses presents under the microscope a remarkable fibrous structure, due to the crystallisation of fine lamellæ of some plagioclase (albite or oligoclase) in the main mass of orthoclase or microcline.[1] Among the accessory minerals developed in gneisses, garnet, tourmaline or schorl, hornblende, pyroxene, cordierite, sillimanite or fibrolite, andalusite, epidote, apatite, graphite, pyrites, zircon, sphene, rutile and magnetite may be enumerated.

One of the most prominent structures in typical gneisses is the banding of their constituents in approximately parallel lenticular layers, which sometimes differ greatly from each other in composition. Thus in the acid varieties, bands of quartz may be seen alternating with bands of orthoclase or other felspar, or with black hornblende or mica. In the more basic kinds, white layers, chiefly composed of plagioclase felspars, may be found separated by darker seams of pyroxene or magnetite. That this separation of mineral constituents has not been produced by any subsequent process of deformation and re-arrangement, but belongs to the original structure of the masses, is rendered highly probable by the discovery of a closely similar arrangement in large bodies of acid and basic eruptive material. Reference has already been made to the banded character of some gabbros (*ante*, p. 232). But the analogy of structure goes still further than the existence of such banding. It has been ascertained that in circumstances which exclude all possibility of subsequent mechanical disturbance the banding in some gabbros exhibits contortion and plication which must have been produced before the final consolidation of the molten material. This remarkable structure is admirably displayed by the Tertiary gabbros of Skye, which so closely in this respect resemble some of the most ancient gneisses that any geologist might well be excused if he at first were to hesitate to believe the rocks to be other than portions of the Archæan gneiss of the north-west of Scotland.[2] There is thus evidently a close parallel between one of the most distinctive characters of gneiss and structures which can be seen in eruptive bosses.

Another line of evidence which links the gneisses with eruptive rocks may be found in the indications, now observed in many places, that true foliated gneisses sometimes behave as intrusive masses which have been injected into other schists and have been accompanied by metamorphism. Professor Lehmann first maintained the true eruptive nature of certain gneisses in the Saxon granulite tract, and this view was subsequently

of pre-Cambrian rocks, Book VI. The carbonaceous gneiss of the Black Forest is described by Professor Rosenbusch in the *Mitt. Badisch. Geol. Landesanst.* IV. i. (1899).

[1] F. Becke (*Tschermak's Min. Mitth.* 1882 (iv.), p. 198) described this structure and named it *microperthite*.

[2] J. J. H. Teall, "The Origin of Banded Gneisses," *Geol. Mag.* 1887, p. 484. A. G., *Trans. Roy. Soc. Edin.* xxxv. (1888), p. 131; *Q. J. G. S.* l. (1894), p. 217; "Sur la Structure rubannée des plus anciens Gneiss et des Gabbros Tertiaires," *Compt. rend. Congr. Géol. Internat. Zurich*, 1894, p. 139. A. G. and J. J. H. Teall, *Q. J. G. S.* l. (1894), p. 645.

further enforced by E. Danzig.[1] In the south-eastern Highlands of Scotland, Mr. George Barrow has traced an intrusion of gneiss which has penetrated a series of schists, producing in them all the characteristic phenomena of contact-metamorphism.[2]

While there can, therefore, be no doubt that some gneisses were originally massive eruptive rocks which have acquired their foliated character by subsequent metamorphism, there can be as little hesitation in regarding other gneisses as having been produced by the alteration of sedimentary strata. The district just referred to as having furnished to Mr. Barrow evidence of an intrusive gneiss, includes a wide area of schists which near the gneiss have acquired a coarse gneissic structure but pass outwards through successive zones of diminishing metamorphism until they become ordinary phyllites. They are of sedimentary origin, and include altered argillaceous rocks, quartzites and limestones. In other regions bands of conglomerate, obviously composed of water-rolled materials, are intercalated among true gneisses as regularly as such materials are among sandstones and shales. Some gneisses, moreover, contain carbonaceous layers which suggest their derivation from former vegetable materials, though the possible source of the carbon in the Archæan rocks may have lain in inorganic processes, to which allusion has already been made. In his discussion of the gneiss of the Black Forest, Professor Rosenbusch came to the conclusion that the carbonaceous substance so abundant in some of these rocks is most likely of organic origin. From time to time what were supposed to be fossils have been reported from the gneiss of different counties. While there can be no doubt that organic remains have really been found in schistose rocks, the materials of which have undergone entire re-arrangement and re-crystallisation (as in the Upper Silurian mica-schist of Southern Norway, described by Reusch), the extreme re-construction which true gneisses have undergone renders the survival of recognisable organic forms in them unlikely.

Where sedimentary strata have been converted into gneiss, the change has sometimes been effected by the re-composition of their intimate structure and the assumption of a new crystalline re-arrangement. In other cases, it has been produced by the introduction of granitic material from without along definite planes, such as those of bedding or of cleavage. This *lit par lit* injection has been studied in detail in the central plateau of France and in the north-west of Scotland.[3]

Many varieties of gneiss have been distinguished by separate names, which in most cases explain themselves. Some are based on peculiarities of structure or composition, as Granite-gneiss, where the schistose arrangement is so coarse as to be unrecognisable, save in a large mass of the rock; Diorite-gneiss, gabbro-gneiss, composed of the materials of a diorite or gabbro but with a coarsely schistose structure; Porphyritic gneiss or Augengneiss, in which large eye-like kernels of orthoclase or quartz are dispersed through a finer matrix and represent larger crystals or crystalline aggregates which have been broken down and dragged along by shearing movements in the rock. Other varieties are named from the occurrence in them of one or more distinguishing minerals, as Hornblende-gneiss (syenitic gneiss), in which hornblende occurs instead of or in addition to mica; Protogine-gneiss, where the ordinary mica is altered into a chloritic or talc-like substance; Sericite-gneiss, a schistose aggregate of sericite, albite, quartz, with less frequently white and black mica and a chloritic mineral;[4] Pyroxene-gneiss, containing an augitic mineral (not of the diallage group) and potash-felspar or potash-soda-felspar or scapolite, with hornblende (which has often crystallised parallel with the augite), brown mica, more or less quartz, and also frequently with

1 Lehmann in *op. cit.*; Danzig, *Mitth. Min. Inst. Kiel*, Band i. pp. 33-79, 99.

2 *Q. J. G. S.* xlix. (1893), pp. 330-358.

3 Michel-Lévy, *Bull. Soc. Géol. France*, xvi. (1888), p. 101. J. Horne and E. Greenly, *Q. J. G. S.* lii. (1896), p. 633. This subject is more fully discussed in Book IV. Part VIII. Sect. ii.

4 K. A. Lossen, *Z. D. G. G.* xix. (1867), p. 565.

garnet, calcite, titanite, &c.;[1] Plagioclase-gneiss, with plagioclase more abundant than orthoclase, sometimes containing hornblende, sometimes augite; Cordierite-gneiss, with the bluish vitreous mineral cordierite, &c.; Graphite-gneiss,[2] containing grains, patches and layers of graphite. Other varieties are Garnet-gneiss, Fibrolite-gneiss, Epidote-gneiss, &c.

The most typical gneisses occur among the so-called "Archæan rocks," of which they form the leading type, and where they probably represent original eruptive rocks. (See Book VI. Part I.) They cover considerable areas in Scandinavia, N.W. Scotland, Bohemia, Bavaria, Erzgebirge, Moravia, Central Alps, Canada, &c. But rocks to which the name of gneiss cannot be refused appear also among the products of the metamorphism of various stratified formations. Such are the gneisses associated with many other crystalline schists among the altered Cambrian and Silurian rocks of Scotland, Norway, and New England, the altered Devonian rocks of the Taunus, and other regions, which will be described in Book IV. Part VIII.

**Granulite**[3] (Eurite-schistoïde, Leptynite of French authors, Weiss-stein)—a fine-grained aggregate, presenting under the microscope a kind of granular mosaic, and composed of pale reddish, yellowish, or white felspar with quartz and small red garnets, occasionally with kyanite, biotite, and microscopic rutile and tourmaline. The felspar, which is the predominant constituent, presents the peculiar fibrous structure referred to in the foregoing description of gneiss (microperthite, microcline), and appears seldom to be true orthoclase. The quartz is conspicuous in thin partings between thicker more felspathic bands, giving a distinctly fissile character to the mass. A dark variety, interstratified with the normal rock, is distinguished by the presence of microscopic augite or diallage (Augitgranulite of Saxony). Granulite occurs in bands among the gneiss and other members of the crystalline schist series in Saxony, Bohemia, Lower Austria, the Vosges, and Central France. The term "granulite" is also employed in a structural sense to denote a rock which has been crushed down by dynamic metamorphism, and has acquired this characteristic fine granular structure. (Pp. 130, 245, 248.)

[1] The occurrence of augite as an abundant constituent of some gneisses has been made known by microscopic research. Rocks of this nature occur in Sweden (A. Stelzner, *N. Jahrb.* 1880, ii. p. 103), and have been fully described from Lower Austria (F. Becke, *Tschermak's Min. Mitth.* iv. 1882, pp. 219-365). They are likewise well developed among the oldest gneisses of the north-west of Sutherland in Scotland.

[2] Graphite is abundant in some gneisses, as for example in those of Canada. The subject of its distribution has been discussed particularly by Dr. E. Weinschenk. See among his contributions, 'Zur Kenntniss der Graphitlagerstätten des Bayerisch-böhmischen Grenzgebirges,' Munich, 1897.

[3] Michel-Lévy has proposed to reserve the names "Leptynite" for schistose and "Granulite" for eruptive rocks. *B. S. G. F.* 3rd ser. ii. pp. 177, 189; iii. p. 287; iv. p. 730; vii. p. 760; Lory, *op. cit.* viii. p. 14. Scheerer, *Neues Jahrb.* 1873, p. 673. Dathe, *N. Jahrb.* 1876, p. 225; *Z. D. G. G.* 1877, p. 274. Details regarding the great development of the granulite of Saxony (Granulitgebirge) will be found in the explanatory pamphlets published with the sheets of the Geological Survey of Saxony, especially those of sections Rochlitz, Geringswalde, and Waldheim. The history of the origin of granulite is discussed by J. Lehmann in his 'Untersuchungen über die Entstehung der Altkrystall. Schiefergesteine.'

| | I. | II. | III. | IV. | V. | VI. | VII. | VIII. | IX. | X. |
|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 58·12 | 73·64 | 68·27 | 45·70 | 46·31–50·46 | 50·81–58·66 | 62·55–83·27 | 55·61–82·38 | 56·44–75·91 | 69·94–76·85 |
| $Al_2O_3$ | 22·73 | 11·25 | 14·03 | 16·53 | 4·31–18·38 | 3·65– 9·26 | 8·19–20·23 | 11·84–18·60 | 9·42–21·60 | 9·75–14·52 |
| $Fe_2O_3$ | 6·83 | 6·24 | 0·46 | 4·63 | 1·56–18·62 | 0·81– 5·79 | 0·38– 4·27 | 2·87–11·98 | 0·89– 7·75 | 0·85– 3·31 |
| FeO | 0·55 | 1·04 | 4·68 | 3·89 | 3·73–18·07 | 1·04– 7·38 | 0·26– 3·72 | 2·28– 6·54 | 1·22–12·30 | 2·18– 5·08 |
| MnO | ... | none | 0·04 | ... | 0·48 | ... | 0·20– 0·48 | ... | ... | 1·83 |
| MgO | 2·31 | 1·57 | 2·23 | 9·57 | 2·04–22·79 | 22·36–30 11 | 0·32– 2·62 | 0·95– 4·60 | 0·01– 3·70 | 0·09– 1·60 |
| CaO | 0·21 | 0·36 | 3·89 | 4·28 | 7·16–14·76 | 0·94–11·25 | 0·34– 8 53 | 0·71– 2·66 | 0·15–13·15 | 0·45– 2·84 |
| $Na_2O$ | 0·69 | 3·04 | 2·29 | 0·55 | 0·89– 4·27 | ... | 0·62– 4·84 | 0·36– 4·02 | 0·46– 4·42 | 1·72– 3·98 |
| $K_2O$ | 3·46 | 1·42 | 3·35 | 3·82 | 0·10– 1·41 | ... | 1·70– 8·12 | 0·83– 4·69 | 1·23– 4·35 | 0·97– 6·55 |
| $Li_2O$ | ... | ... | trace | ... | ... | ... | ... | ... | ... | ... |
| $TiO_2$ | ... | trace | 0·57 | ... | 0·03– 2·80 | ... | ... | ... | 0·53– 1·70 | ... |
| SrO | ... | ... | trace | ... | ... | ... | ... | ... | ... | ... |
| $P_2O_5$ | ... | ... | 0·21 | ... | ... | ... | ... | ... | ... | ... |
| BaO | ... | ... | 0·08 | ... | ... | ... | ... | ... | ... | ... |
| $CO_2$ | ... | ... | ... | 5·95 | ... | | ... | ... | ... | ... |
| Ignition | 4·22 | 1·98 | ... | ... | ... | 2·60– 6·07 | .. | 2·27 | ... | ... |
| $H_2O$ | ... | ... | 1·06 | 4·70 | $\left.\begin{matrix}\\\\\end{matrix}\right\}$ 0·21–4·59 | | 0·40– 1·42 | 0·52– 2·04 | 0·02– 2·10 | 0·22– 1·15 |
| | 99·12 | 100·54 | 100·16 | 99·62 | | | | | | |

I. Green silky Phyllite, Hasenschwanzbruch, near Lössnitz, Saxony. Dalmer, Kart. Sachsen, Sect. Lossnitz.
II. Quartzite, Pigeon Point, Minnesota. Analysed by R. B. Riggs, *B. U. S. G. S.* No. 168, p. 78.
III. Hornfels, Agua Fria Creek, Mariposa County, California. Analysed by W. F. Hillebrand, *B. U. S. G. S.* No. 168, p. 210 : contains quartz, brown mica, iron-ore and plagioclase : *17th Ann. Rep. U. S. G. S.* part i. p. 691.
IV. Silvery Gabbro-schist formed out of gabbro, Sturgeon Falls, Michigan. G. H. Williams, *B. U. S. G. S.* No. 62 (1890), p. 76.
V. Range of 8 analyses of Amphibolites cited by Zirkel, 'Lehrbuch,' iii. p. 341. Manganous oxide is distinguished in only one analysis, and titanic acid only in four.
VI. Range of 5 analyses of Talc-schists, *ibid.* p. 329. The ferric and ferrous oxides are not separated in two of the analyses.
VII. Range of 7 analyses of Scandinavian Hälleflintas, *ibid.* p. 264. Manganous oxide is noted in only two of these analyses.
VIII. Range of 5 analyses of Mica-schists, *ibid.* p. 283. Ferric oxide only is noted in two analyses, and ferrous oxide only in the other three. The loss on ignition is stated only in one case, the water is given in four.
IX. Range of 14 analyses of different types of Gneiss, *ibid.* p. 223. The iron oxides are separately given in six of the columns ; in three cases ferric oxide only is mentioned, while in five only the ferrous oxide appears.
X. Range of 9 analyses of various Granulites, *ibid.* p. 247. The iron oxides are separately stated in only two cases ; the ferric is given in four of the analyses, and the ferrous in the other four.

# BOOK III.

## DYNAMICAL GEOLOGY.

DYNAMICAL GEOLOGY investigates the processes of change at present in progress upon the earth, whereby modifications are made on the structure and composition of the crust, on the relations between the interior and the surface, as shown by volcanoes, earthquakes, and other terrestrial disturbances, on the distribution of land and sea, on the outlines of the land, on the form and depth of the sea-bottom, on marine currents, and on climate. Bringing before us, in short, the whole range of geological activities, it leads to precise notions regarding their relations to each other, and the results which they achieve. A knowledge of this branch of the subject is thus the essential groundwork of a true and fruitful acquaintance with the principles of geology, which are founded on the postulate that the study of the present order of nature provides a key for the interpretation of the past.

The operations considered by Dynamical Geology may be regarded as a vast cycle of change, into the investigation of which the student may break at any point, and round which he may travel, only to find himself brought back to his starting-point. It is a matter of comparatively small moment at what part of the cycle the inquiry is begun. The changes seen in action will always be found to have resulted from some that preceded, and to give place to others that follow them.

At an early time in the earth's history, anterior to any of the periods of which a record remains in the visible rocks, the chief sources of geological energy probably lay within the earth itself. The planet still retained much of its initial heat, and in all likelihood was the theatre of great chemical changes. As it cooled, and as the superficial disturbances due to internal heat and chemical action became less marked, the influence of the sun, which must always have operated, and which in early geological times may have been more effective than it afterwards became, would then stand out more clearly, giving rise to that wide circle of surface changes wherein variations of temperature and the circulation of air and water over the surface of the earth come into play.

In the pursuit of his inquiries into the past history and into the

present economy of the earth, the student must needs keep his mind ever open to the reception of evidence for kinds, and especially for degrees, of action which he had not before encountered. Human experience has been too short to allow him to assume that all the causes and modes of geological change have been definitely ascertained. Besides the fact that both terrestrial and solar energy were once probably more intense than now, there may remain for future discovery evidence of former operations by heat, magnetism, chemical change, or other agency, that may explain phenomena with which geology has to deal. Of the influences, so many and profound, which the sun exerts upon our planet, we can as yet only perceive a little. Nor can we tell what other cosmical influences may have lent their aid in the revolutions of geology.

Much light has been and will assuredly yet be cast on this domain of the science by experimental research, whereby the nature and results of geological processes are imitated artificially as closely as the conditions of each problem will permit. Many of the operations of nature proceed on so gigantic a scale and under conditions so entirely different from any which we can even approximately reproduce, that in these departments of inquiry little perhaps may be hoped for from any experiments. But in many other cases it is possible to repeat with a fair approach to accuracy the processes of nature, to watch their progress and introduce many modifying influences which help us in some measure to comprehend at once the simplicity and infinite complexity of nature's working. The beginnings of experimental geology took their rise towards the end of the eighteenth century, when De Saussure set himself to study the possible derivation of rocks by fusing samples of them and judging whether, as had been alleged, some had arisen from the melting of others.[1] But the man who first realised that the processes of nature might to a considerable extent be imitated by man, and that the validity of geological theories might be tested in the laboratory, was Sir James Hall, who described a series of ingenious experiments by which he demonstrated the possibility of producing either a vitreous or a stony condition in fused rocks, according to the rate at which they are allowed to cool. He likewise succeeded in fusing limestone without the loss of its carbonic acid, and he showed by a simple device of layers of clay how the plications of the terrestrial crust could be accounted for.[2]

Since Hall's time a century has passed away, and much has been done in this interval along the lines indicated by him, as well as along others which the onward march of science has opened up. One of the most illustrious of his successors was the late Professor Daubrée, whose researches have greatly advanced our knowledge of every department of geological dynamics which he undertook to investigate. His great work, 'Géologie Expérimentale,' in which towards the end of his distinguished career he gathered together the chief results of his labours, will ever remain a classic in geological literature. Many other workers have contributed their share to experimental research, and to some of their more important

[1] 'Voyages dans les Alpes,' i. (1779), pp. 122-127.

[2] *Trans. Roy. Soc. Edin.* v. (1798), p. 43 ; vi. p. 71 ; vii. p. 79 ; x. p. 314.

papers reference will be made in subsequent pages.[1] But there is still room for a much more extensive adoption of the experimental method. Probably no branch of geology is likely to make more rapid advances in the future than the dynamical department will do by the resolute endeavour to imitate and vary under different conditions every geological process that is capable of imitation.

In the present state of knowledge, all the geological energy upon and within the earth must ultimately be traced back to the primeval energy of the parent nebula, or sun. There is, however, a certain propriety and convenience in distinguishing between that part of it which is due to the survival of some of the original energy of the planet, and that part which arises from the present supply of energy received day by day from the sun. In the former case, the geologist has to deal with the interior of the earth and its reaction upon the surface; in the latter, he is called upon to study the surface of the earth, and to some extent its reaction on the interior. This distinction allows of a broad treatment of the subject under two divisions:—

I. Hypogene or Plutonic Action—the changes within the earth, caused by original internal heat and by chemical action.

II. Epigene or Surface Action—the changes produced on the superficial parts of the earth, chiefly by the circulation of air and water set in motion by the sun's heat.

## PART I. HYPOGENE ACTION,

*An Inquiry into the Geological Changes in Progress beneath the Surface of the Earth.*

In the discussion of this branch of the subject, it is useful to carry in the mind the conception of a globe still intensely hot within, radiating heat into space, and consequently contracting in bulk. Portions of molten rock from inside are from time to time poured out at the surface. Sudden shocks are generated, by which earthquakes are propagated to and along the surface. Wide geographical areas are upraised or depressed. In the midst of these movements, the rocks of the crust are fractured, squeezed, sheared, crumpled, rendered crystalline, and even fused.

### Section i. Volcanoes and Volcanic Action.[2]

#### § 1. Volcanic Products.

The term volcanic action (volcanism or volcanicity) embraces all the phenomena connected with the expulsion of heated materials from the

[1] Special reference may be made here to the great services rendered to this department of geology by Professor E. Reyer of Vienna. For many years he has carried on a series of experiments in illustration of many different geological processes, publishing his results from time to time in a succession of suggestive memoirs. Among his contributions are 'Beitrag zur Physik der Eruptionen,' Vienna, 1877; 'Theoretische Geologie,' 1888; 'Geologische und Geographische Experimente,' 1892-94.

[2] The student is referred to the following general works on the phenomena of volcanoes: Scrope, 'Considerations on Volcanoes,' London, 1825; 'Volcanoes,' London, 2nd edit.

interior of the earth to the surface. Among these phenomena, some possess an evanescent character, while others leave permanent proofs of their existence. It is naturally to the latter that the geologist gives chief attention, for it is by their means that he can trace former phases of volcanic activity in regions where, for many ages, there have been no volcanic eruptions. In the operations of existing volcanoes he can observe only superficial manifestations of volcanic action. But examining the rocks of the earth's crust, he discovers that amid the many terrestrial revolutions which geology reveals, the very roots of former volcanoes have been laid bare, displaying subterranean phases of volcanism which cannot be studied in any modern volcano. Hence an acquaintance only with active volcanoes will not afford a complete knowledge of volcanic action. It must be supplemented and enlarged by an investigation of the traces of ancient volcanoes preserved in the crust of the earth. (Book IV. Part VII.)

The word "volcano" is applied to a conical hill or mountain (composed mainly or wholly of erupted materials), from the summit and often also from the sides of which hot vapours issue, and ashes and streams of molten rock are intermittently expelled. The term "volcanic" designates all the phenomena essentially connected with one of these channels of communication between the surface and the heated interior of the globe. Yet there is good reason to believe that the active volcanoes of the present day do not afford by any means a complete type of volcanic action. The first effort in the formation of a new volcano is to find egress for its pent-up vapours, through the earth's crust to the outer surface. This may be effected sometimes by the drilling of a funnel in the crust, the materials of which are violently expelled above ground; at other times by the production of a rent or fissure in the crust, through some weaker part of which the volcanic vapours, lava, or ashes are ejected. In many parts of the earth, alike in the Old World and the

1872; 'Extinct Volcanoes of Central France,' London, 1858; "On Volcanic Cones and Craters," *Q. J. G. S.* 1859. Daubeny, 'A Description of Active and Extinct Volcanoes,' 2nd edit. London, 1858. Darwin, 'Geological Observations on Volcanic Islands,' 2nd edit. London, 1876. A. von Humboldt, 'Ueber den Bau und die Wirkung der Vulkane,' Berlin, 1824. L. von Buch, "Ueber die Natur der vulkanischen Erscheinungen auf den Canarischen Inseln," *Poggend. Annalen* (1827), ix. x.; "Ueber Erhebungskratere und Vulkane," *Poggend. Annalen* (1836), xxxvii. E. A. von Hoff, 'Geschichte der durch Ueberlieferung nachgewiesenen natürlichen Veränderungen der Erdoberfläche' (part ii. "Vulkane und Erdbeben"), Gotha, 1824. C. W. C. Fuchs, 'Die vulkanischen Erscheinungen der Erde,' Leipzig, 1865. R. Mallet, "On Volcanic Energy," *Phil. Trans.* 1873. J. Schmidt, 'Vulkanstudien,' Leipzig, 1874. Sartorius von Waltershausen and A. von Lasaulx, 'Der Aetna, 4to, Leipzig, 1880. E. Reyer, 'Beitrag zur Physik der Eruptionen,' Vienna, 1877; 'Die Euganeen; Bau und Geschichte eines Vulkanes,' Vienna, 1877. Fouqué, 'Santorin et ses Éruptions,' Paris, 1879. Judd, 'Volcanoes,' 1881. G. Mercalli, 'Vulcani e Fenomeni vulcanici in Italia,' Milan, 1883. Ch. Vélain, 'Les Volcans,' Paris, 1884. J. D. Dana, 'Characteristics of Volcanoes,' 1890. E. Hull, 'Volcanoes Past and Present,' 1892. H. J. Johnston-Lavis, 'The South Italian Volcanoes,' Naples, 1891. A. Stübel, 'Die Vulkanberge von Ecuador,' Berlin, 1897. References will be found in succeeding pages to other and more special memoirs, and to the literature of different important volcanic centres.

New, there have been periods in the earth's history when the crust was rent into innumerable fissures over areas thousands of square miles in extent, and when the molten rock, instead of issuing, as it does at most modern volcanoes, in narrow streams from a central elevated cone, welled out from these rents or from numerous small vents along their course, and flooded enormous tracts of country without forming any mountain or conspicuous volcanic cone in the usual sense of these terms. Of these "fissure-eruptions," apart from central volcanic cones, no examples appear to have occurred within the times of human history, except in Iceland, where vast lava-floods issued from a fissure in 1783 (p. 342). They can best be studied from the remains of former convulsions. Their importance, however, has not yet been generally recognised in Europe, though acknowledged in America, where they have been largely developed. Much still remains to be done before their mechanism is as well understood as that of the lesser and more familiar type with which man has been acquainted from the earliest days, since it is so well displayed in Vesuvius, Etna, and the Lipari Islands. In the succeeding narrative an account is first presented of the Vesuvian type of volcano and its products; and in § 3, ii., some details are given of the general aspect and character of fissure-eruptions.

The openings by which heated materials from the interior now reach the surface include volcanoes (with their various associated orifices) and hot springs.

The prevailing conical form of a volcano is that which the ejected materials naturally assume round the vent of eruption. In the most familiar or Vesuvian type, the summit of the cone is truncated (Figs. 38, 44), and presents a cup-shaped or caldron-like cavity, termed the crater, at the bottom of which is the top of the main funnel or pipe of communication with the heated interior. A volcano, when of small size, may consist merely of one cone; when of the largest dimensions, it forms a huge mountain, with many subsidiary cones and many lateral fissures or pipes, from which the heated volcanic products are given out. Mount Etna (Fig. 38), rising from the sea to a height of 10,840 feet, and supporting, as it does, some 200 minor cones, many of which are in themselves considerable hills, is a magnificent example of a colossal volcano.[1] Some of the most gigantic volcanoes, such, for instance, as most of those of Ecuador, including the great Cotopaxi, have no craters, successive eruptions taking place from their flanks.

[1] The structure and history of ETNA are fully described in the great work of Sartorius von Waltershausen and A. von Lasaulx cited on p. 263—a treasure-house of facts in volcanic geology. The bibliography of the mountain up to 1891 is given in Dr. Johnston-Lavis, 'The South Italian Volcanoes,' Naples, 1891. See also G. F. Rodwell, 'Etna, a History of the Mountain and its Eruptions,' London, 1878; O. Silvestri, 'Un Viaggio all' Etna,' 1879. 'Etna, Sicilia ed isole volcaniche adiacenti,' Catania, 1890. Notices of recent eruptions of the mountains will be found in *Nature*, vols. xix. xx. xxi. xxii. xxv. (observatory on Etna, p. 394), xxvii. xlvi. xlvii. lv. lx.; *Compt. rend.* lxvi. The work of Mercalli, cited on p. 263, gives descriptions of this and the other Italian volcanic centres. See for the eruption of 1892, Mercalli, *Att. Soc. Ital. Sci. Nat.* xxxiv. (1893); A. Baltzer, *Neues Jahrb.* i. (1893), p. 75.

The materials erupted from volcanic vents may be classed as (1) gases and vapours, (2) water, (3) lava, (4) fragmentary substances. A brief summary under each of these heads may be given here; the share

Fig. 38.—View of Etna from the Torre Archirafi (Sartorius von Waltershausen).

taken by the several products in the phenomena of an active volcano is described in § 2.

1. **Gases and Vapours** exist dissolved in the molten magma within the earth's crust. They play an important part in volcanic activity, some of them showing themselves in the earliest and most energetic stages of

a volcano's history, while others continue to issue from the ground for centuries after all other subterranean action has ceased. By much the most abundant of them all is water-gas, which, ultimately escaping as steam, has been estimated to form $\frac{999}{1000}$ths of the whole cloud that hangs over an active volcano (Fig. 39). In great eruptions, steam rises in prodigious quantities, and is rapidly condensed into a heavy rainfall. M. Fouqué calculated that, during 100 days, one of the parasitic cones on Etna had ejected vapour enough to form, if condensed, 2,100,000 cubic metres (462,000,000 gallons) of water. The disastrous eruptions of St. Vincent and Martinique in May 1902 appear to have been due to

Fig. 39.—View of Vesuvius as seen from Naples during the eruption of 1872, showing the dense clouds of condensed aqueous vapour.

the discharge of enormous quantities of superheated steam, mingled probably with sulphurous acid, and largely loaded with incandescent lava-dust and sand, lapilli and scoriæ. But even from volcanoes which, like the Solfatara of Naples, have been dormant for centuries, steam sometimes still rises without intermission and in considerable volume. Jets of vapour rush out from clefts in the sides and bottom of a crater with a noise like that made by the steam blown off by a locomotive. The number of these funnels or "fumaroles" is often so large, and the amount of vapour so abundant, that only now and then, when the wind blows the dense cloud aside, can a momentary glimpse be had of a part of the bottom of the crater; while at the same time the rush and roar of the escaping steam remind one of the din of some vast factory. Aqueous vapour rises likewise from rents on the outside of the volcanic cone. It issues so copiously from some flowing lavas that the stream of rock may be almost concealed from view by the cloud; and

it continues to escape from fissures of the lava, far below the point of exit, for a long time after the rock has solidified and come to rest. So saturated are many molten lavas with water-vapour that Scrope thought that they owed their mobility to this cause.[1] In the deep volcanic magma the water-substance must be far above its critical temperature, which is about 773° Fahr.

Probably seldom is the steam mere pure vapour of water, though when it condenses into copious rain it is fresh and not salt water.[2] It is associated with other vapours and gases disengaged from the potent chemical laboratory underneath. There seems to be always a definite order in the appearance of these vapours, though it may vary for different volcanoes. The hottest and most active "fumaroles," or vapour-vents, may contain all the gases and vapours of a volcano, but as the heat diminishes the series of gaseous emanations is reduced. Thus in the Vesuvian eruption of 1855-56 the lava, as it cooled and hardened, gave out successively vapours of hydrochloric acid, chlorides, and sulphurous acid; then steam; and, finally, carbon-dioxide and combustible gases.[3] More recent observations tend to corroborate the deductions of C. Sainte-Claire Deville that the nature of the vapours evolved depends on the temperature or degree of activity of the volcanic orifice, chlorine (and fluorine) emanations indicating the most energetic phase of eruptivity, sulphurous gases a diminishing condition, and carbonic acid (with hydrocarbons) the dying out of the activity.[4] A "solfatara," or vent emitting

[1] 'Considerations on Volcanoes' (1825), p. 110.

[2] At the island of Pantelleria, to the south-west of Sicily, the vapour is pure enough to be condensed and used as drinking-water by the natives. On atmospheric waters in fumaroles, with special reference to Vulcano and Stromboli, see G. de Stefani, *Boll. Soc. Geol. Ital.* xix. (1900), pp. 295-320.

[3] C. Sainte-Claire Deville and Leblanc, *Ann. Chim. et Phys.* lii. (1858), p. 19 *et seq.* For accounts of VESUVIUS and its eruptions, besides the general works already cited on p. 263, consult J. Phillips' 'Vesuvius,' 1869; J. L. Lobley, 'Mount Vesuvius,' 1889; J. Schmidt, 'Die Eruption des Vesuv. 1855,' Vienna, 1856; Mercalli's 'Vulcani,' &c.; H. J. Johnston-Lavis, *Q. J. G. S.* xl. 35; *Geol. Mag.* 1888, p. 445. A diary of the volcano's behaviour for six months is given in *Nature*, xxvi.; one for four years (1882-1886) by Dr. Johnston-Lavis, 'Spettatore del Vesuvio,' Naples, 1887. See also his reports in *Nature*, xliv. (1891), pp. 160, 320, 352; lii. (1895), p. 342. A valuable series of reports on the mountain by the same author will be found in recent volumes of the *Reports of the British Association* (1885-95); and a large detailed map of the volcano, also by him, is published by Philip, London, 1891. The record of the volcano's activity by Professor Mercalli will be found year by year in the *Boll. Soc. Sismolog. Ital.* from vol. i. onwards. Some important papers by R. V. Matteucci are in the same Bolletino, see vols. iv. v. vi.; also *Rend. R. Acad. Sci. Fis. e Mat. Napoli*, vols. for 1891, 1897, 1898, 1899; *Compt. rend.* cxxix. 3rd July 1899; *Rend. Acad. Lincei.* viii. (1899), p. 168; *Tschermak's Mitth.* xv.; (1895), pp. 77, 325; G. de Lorenzo, *Z. D. G. G.* xlix. (1897), p. 561; *Bol. Soc. Geol. Ital.* xvii. (1898), p. 257; P. Franco, *op. cit.* xviii. (1899), p. 41.

[4] He distinguished volcanic emanations according to their order of appearance as regards time, nearness to the vent, and temperature, viz.:—1. Dry fumaroles (without steam), where anhydrous chlorides are almost the only discharge, and where the temperature is very high (above that of melted zinc). 2. Acid fumaroles, with sulphurous and hydrochloric acids and steam. 3. Alkaline (ammoniacal) fumaroles; temperature about 100° C.; abundant

only gaseous discharges, is believed to pass through these successive stages. Wolf observed that on Cotopaxi, while hydrochloric acid, and even free chlorine, escaped from the summit of the cone, sulphuretted hydrogen and sulphurous acid issued from the middle and lower slopes.[1] Fouqué's studies at Santorin have shown also that from submarine vents a similar order of appearance obtains among the volcanic vapours, hydrochloric and sulphurous acids being only found at points of emission having a temperature above 100° C., while carbon-dioxide, sulphuretted hydrogen, and nitrogen occur at all the fumaroles, even where the temperature is not higher than that of the atmosphere.[2]

The following are the chief gases and acids evolved at volcanic fumaroles :—Hydrochloric acid is abundant at Vesuvius, and probably at many other vents whence it has not been recorded. It is recognisable by its pungent, suffocating fumes, which make approach difficult to the clefts from which it issues. Sulphuretted hydrogen and sulphurous acid are distinguishable by their odours. The liability of the former gas to decomposition leads to the deposition of a yellow crust of sulphur ; occasionally, also, the production of sulphuric acid is observed at active vents. From observations made at Vesuvius in May 1878, Mr. Siemens concluded that vast quantities of free hydrogen or of combustible compounds of this gas exist dissolved in the magma of the earth's interior, and that these, rising and exploding in the funnels of volcanoes, give rise to the detonations and clouds of steam.[3] At the eruption of Santorin in 1866, the same gases were also distinctly recognised by Fouqué, who for the first time established the existence of true volcanic flames. These were again studied spectroscopically in the following year by Janssen, who found them to arise essentially from the combustion of free hydrogen, but with traces of chlorine, soda, and copper. Fouqué determined by analysis that, immediately over the focus of eruption, free hydrogen formed 30 per cent of the gases emitted, but that the proportion of this gas rapidly diminished with distance from the active vents and hotter lavas, while at the same time the proportion of marsh-gas and carbon-dioxide rapidly increased. The gaseous emanations collected by him were found to contain abundant free oxygen as well as hydrogen. One analysis gave the following results: carbon-dioxide 0·22, oxygen 21·11, nitrogen 21·90, hydrogen 56·70, marsh-gas 0·07=100·00. This gaseous mixture, on coming in contact with a burning body, at once ignites with a sharp explosion. Fouqué infers that the water-vapour of volcanic vents may exist in a state of dissociation within the molten magma whence lavas rise.[4] Carbon-dioxide rises chiefly (*a*) after an eruption has ceased and the volcano relapses into quiescence ; or (*b*) after volcanic action has otherwise become extinct. Of the former phase, instances are on record at Vesuvius where an eruption has been followed by the emission of this gas so copiously from the ground as to suffocate hundreds of hares, pheasants, and partridges. Of the second phase, good examples are supplied by the ancient volcanic regions of the Eifel and Auvergne, where the gas still rises in prodigious quantities. Bischof estimated that the volume of carbonic acid evolved in the Brohl Thal amounts to 5,000,000 cubic

steam with chloride of ammonium. 4. Cold fumaroles ; temperature below 100° C., with nearly pure steam, accompanied by a little carbon-dioxide, and sometimes sulphuretted hydrogen. 5. Mofettes ; emanations of carbon-dioxide with nitrogen and oxygen, marking the last phase of volcanic activity.

[1] *Neues Jahrb.* 1878, p. 164.

[2] 'Santorin et ses Éruptions,' Paris, 1879 ; W. Libbey, *Amer. Journ. Sci.* xlvii. (1894), p. 371.

[3] *Monatsb. K. Preuss. Akad.* 1878, p. 588.

[4] Fouqué, 'Santorin et ses Éruptions,' p. 225.

feet, or 300 tons of gas in one day. Nitrogen, derived perhaps from the decomposition of atmospheric air dissolved in the water which penetrates into the volcanic foci, has been frequently detected among the gaseous emanations. At Santorin it was found to form from 4 to 88 per cent of the gas obtained from different fumaroles.[1] Fluorine and iodine have likewise been noticed. Vapours of sulphur and boric acid prevail at Vulcano. Selenium is found as a sulphur selenide at the vent of Vulcano, and was detected together with iodine and bromine in the fumaroles of the Vesuvian eruption of July 1895.[2] The fumaroles of Vulcano have been carefully studied by A. Cossa and other chemists, with the result of showing a series of at least twenty elements and combinations of elements which, besides those just named, include chlorides of sodium, ammonium and iron, sulphate of lithium, glauberite, alum containing thallium, rubidium and cæsium, hieratite (a compound of fluorides of potassium and silicon), realgar, tellurium, cobalt, zinc, tin, bismuth, lead, copper and phosphorus.[3]

With the volcanic gases and vapours are associated many substances which, sublimed by the volcanic heat or resulting from reactions among the escaping vapours, appear as Sublimates along crevices wherein they reach the air and are cooled. Besides sulphur, there are several chlorides (particularly that of sodium, and less abundantly those of potassium, iron, copper and lead); also free sulphuric acid, salammoniac, specular iron, oxide of copper, boracic acid, alum, sulphate of lime, felspars, pyroxene and other substances. Carbonate of soda occurs in large quantities among the fumaroles of Etna. Sodium-chloride sometimes appears so abundantly that wide spaces of a volcanic cone, as well as of the newly erupted lava, are crusted with salt, which can even be profitably removed by the inhabitants of the district. Considerable quantities of chlorides, &c., may thus be buried between successive sheets of lava, and in long subsequent times may give rise to mineral springs, as has been suggested with reference to the saline waters which issue from volcanic rocks of Old Red Sandstone and Carboniferous age in Scotland.[4] The iron-chloride forms a bright yellow and reddish crust on the crater walls, as well as on loose stones on the slopes of the cone. Specular iron, from the decomposition of iron-chloride, forms abundantly as thin lamellæ in the fissures of Vesuvian lavas. In the spring of 1873 the author observed delicate brown filaments of tenorite (copper-oxide, CuO) forming in clefts of the crater of Vesuvius. They were upheld by the upstreaming current of vapour until blown off by the wind. Professor Fouqué has described tubular vents in the lavas of Santorin with crystals of anorthite, sphene, and pyroxene, formed by sublimation. In the lava stalactites of Hawaii needle-like fibres of breislakite abound. M. Lacroix has detected in a long-extinct fumarole at Royat in Auvergne crystals of hæmatite, biotite, augite, labradorite, andesine and anorthose, and has pointed out that the elements of these silicates have been mainly supplied by the rocks on which they have crystallised, under the influence of the volcanic vapours.[5]

The various vapours and gases emitted at active volcanic vents not only act corrosively on the rocks through which they pass (*postea*, p. 313), but from time to time injuriously affect the vegetation for some distance around. Thus at Vesuvius, where large volumes of steam are given off, charged with hydrochloric acid, the condensation of this steam or the passage of rain through it brings down the acid to the ground, seriously damaging corn, vines, and other vegetation on the slopes of the mountain. Moreover, the wind sometimes carries the deleterious moisture far over the country. In

[1] Fouqué, *loc. cit.* It was found to constitute 73·53 per cent of the gas at the Grotta di S. Germano in the crater of Agnano near Naples. Sainte-Claire Deville and Leblanc, *op. cit.*

[2] R. V. Matteucci, *Rend. Acad. Napoli*, 1897. *Nature*, lvi. p. 472. In the eruption of 1900, salammoniac was detected by the same observer. *Compt. rend.* cxxxi. (1900), p. 964.

[3] A. Cossa, *Atti Acad. Lincei* (3), ii. 1878.

[4] *Proc. Roy. Soc. Edin.* ix. p. 367.

[5] *Compt. rend.* May 1898.

the spring of 1902, for example, the young shoots of the hazel-trees were entirely destroyed at Palma, a distance of twelve miles from the crater. Again, at Santorin it was observed during the eruption of June 1866 that while the fall of dry volcanic dust did not sensibly affect the vegetation, injury became serious when rain fell with the dust, the vines along the track of the smoke-cloud being then withered up, as if they had been burnt.[1]

In reference to the gases and vapours given off at volcanic vents it is interesting to observe that some of the more frequent and important of them are precisely those which fill the minute pores of volcanic and plutonic rocks of all ages (*ante*, p. 142), and which appear to have been largely effective in the processes of crystallisation and differentiation of igneous magmas. They were named long ago "mineralising agents" by Élie de Beaumont, whose views as to their importance have been confirmed by later research. All the emanations and sublimations that accompany the uprise of eruptive rocks have been grouped under the general term "pneumatolitic."[2]

Attention may be directed here to M. Moissan's important researches into the combinations of metals with carbon, which have brought to light some suggestive facts in regard to this subject. He has succeeded in forming artificially a large series of metallic carbides, one class of which is readily decomposed by cold water, yielding various gaseous or liquid hydrocarbons. Thus aluminium dissolves carbon, and in contact with water yields alumina and pure marsh-gas or fire-damp. The association of mineral oil, marsh-gas, and other hydrocarbons and of carbonic acid in old volcanic districts may thus point to the continuous decomposition of such carbides by access of water. M. Moissan suggests that some explosive volcanic phenomena may even be due to the same cause. The latest emanations from waning vents might range from asphalt and mineral oil up to the most complete oxidation in carbonic acid.[3]

2. **Water.**—Abundant discharges of water accompany some volcanic explosions. Three sources of this water may be assigned:—(1) from the melting of snow by a rapid accession of temperature previous to or during an eruption; this takes place from time to time on Etna, in Iceland, and among the snowy ranges of the Andes, where the cone of Cotopaxi is said to have been entirely divested of its snow in a single night by the heating of the mountain; (2) from the condensation of the vast clouds of steam which are discharged during an eruption; this undoubtedly is the chief source of the destructive torrents so frequently observed to form part of the phenomena of a great volcanic explosion; and (3) from the disruption of reservoirs of water filling subterranean cavities, or of lakes occupying crater-basins; this has several times been observed among the South American volcanoes,[4] where immense quantities of dead fish, which inhabited the water, have been swept down with the escaping torrents. The volcano of Agua, in Guatemala, received its name from the disruption of a crater-lake at its summit by an earthquake in 1540, whereby a vast and destructive debacle of

[1] Fouqué, 'Santorin,' p. 81.

[2] Prof. Brögger includes under this term the minerals produced by the mineralising agents, whether within the magma itself or in fissures or crevices among the surrounding rocks.

[3] *Proc. Roy. Soc.* lx. (1897), p. 156; and *postea*, p. 357.

[4] On SOUTH AMERICAN volcanoes see the early descriptions in Humboldt's 'Cosmos'; also the work of Stübel on Ecuador, cited on p. 263; Hettner, *Petermann's Mitth. Ergänz.* No. 104; H. Berger, *op. cit.* xxxvii. p. 246; Moerike, *op. cit.* xl. p. 142; Noguès, *Compt. rend.* cxviii. p. 372; Whymper's 'Travels among the Great Andes.'

water was discharged down the slopes of the mountain.[1] In the beginning of the year 1817 an eruption took place at the large crater of Idjèn, one of the volcanoes of Java,[2] whereby a steaming lake of hot acid water was discharged with frightful destruction down the slopes of the mountain. After the explosion, the basin filled again with water, but its temperature was no longer high.

In many cases, the water rapidly collects volcanic dust as it rushes down, and soon becomes a pasty mud; or it issues at first in this condition from the volcanic reservoirs after violent detonations. Hence arise what are termed **mud-lavas**, or aqueous lavas, which in many respects behave like true lavas. This volcanic mud eventually consolidates into one of the numerous forms of tuff, a rock which, as has been already stated (p. 172), varies greatly in the amount of its coherence, in its composition, and in its internal arrangement. Obviously, unless where subsequently altered, it cannot possess a crystalline structure like that of true lava. As a rule, it betrays its aqueous origin by more or less distinct evidence of stratification, by the multifarious pebbles, stones, blocks of rock, tree-trunks, branches, shells, bones, skeletons, &c., which it has swept along in its course and preserved within its mass. Sections of this compacted tuff may be seen at Herculaneum.[3] The *trass* of the Brohl Thal and other valleys in the Eifel[4] district, referred to on p. 175, is another example of an ancient volcanic mud.

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[1] For an account of this mountain see K. v. Seebach, *Abh. Gesell. Wiss. Göttingen*, xxxviii. (1892), p. 216. For descriptions of the volcanoes of CENTRAL AMERICA consult Humboldt's 'Cosmos'; Felix and Lenk, 'Beiträge zur Geologie und Paläontologie der Republik Mexico,' Leipzig, 1890; Sapper, "Die südlichsten Vulkane Mittel-Americas,' *Z. D. G. G.* xliii. p. 1; xlv. pp. 56, 574; A. Dollfuss and E. de Montserrat, 'Voyage géologique dans les Républiques de Guatemala et San Salvador,' Paris, 1868. K. von Seebach, *Abh. K. Ges. Wiss. Göttingen*, xxxviii. (1892). E. Ordoñez, "Les Volcans du Vallé de Santiago," *Mem. Soc. Alzate*, xiv. (1900), p. 299; *ibid.* xi. (1898), p. 325; "Expedicion cientifica al Popocatapetl," *Commiss. Geol. Mexico*, 1895; M. Bertrand, 'Phénomènes volcaniques et tremblements de terre de l'Amérique centrale,' 4to, Paris, 1900; Gosling. *Q. J. G. S.* liii. (1897), p. 221.

[2] For the volcanoes of the EAST INDIES, Junghuhn's 'Java.' Sunda Island and Moluccas, F. Scheider, *Jahrb. Geol. Reichsanst.*, Vienna, xxxv. (1885), p. 1; also the works on Krakatoa quoted on p. 290. On volcanic action in Batavia, *Nature*, l. (1894), p. 620; Wichmann, *Tijdsch. Nederland. Aardr. Gen.* 1890, 1891, 1892, 1898; *Z. D. G. G.* 1893, p. 542; 1897, p. 152; 1900, p. 640. Professor Wichmann has shown reason to believe that the mud eruption said to have been discharged by the Gunung Salak in Java in the year 1699 was really the result of landslips caused by a severe earthquake. *Neues Jahrb.* 1896, ii.

[3] Mallet thought that the so-called "mud-lavas" of Herculaneum and Pompeii were not aqueous deposits (*Journ. Roy. Geol. Soc. Ireland*, vi. (1876), p. 144). But there seems no reason to doubt that while an enormous amount of ashes fell during the eruption of A.D. 79, there were likewise, especially in the later phases of eruption, copious torrents of water that mingled with the fine ash and became "mud-lavas." The sharpness of outline and the absence of any trace of abdominal distension in the moulds of the human bodies found at Pompeii, probably show that these victims of the catastrophe were rapidly enveloped in a firm coherent matrix which could hardly have been mere loose dust. See H. J. Johnston-Lavis, *Q. J. G. S.* xl. p. 89. The solid tuff which filled the theatre at Herculaneum, and which has been partially excavated underground, has enclosed pieces of Roman pottery.

[4] For works on the EIFEL district consult Hibbert, 'History of the Extinct Volcanoes of the Basin of Neuwied on the Lower Rhine,' Edin. 1832. Von Dechen, 'Geognostischer Führer zu dem Laacher See,' Bonn, 1864; 'Geognostischer Führer in das Siebengebirge am Rhein,' Bonn, 1861. Vogelsang, "Vulkane der Eifel," *Neues Jahrb.* 1870, pp. 199, 326, 460. H. Behrens, *Ann. École polyt. Delft*, 1888, pp. 134-148.

3. **Lava.**—The term lava is applied generally to all the molten rocks of volcanoes.[1] The use of the word in this broad sense is of great convenience in geological descriptions, by directing attention to the leading character of the rocks as molten products of volcanic action, and obviating the confusion and errors which are apt to arise from an ill-defined or incorrect lithological terminology. Precise definitions of the rocks, such as those above given in Book II., can be added when required. A few remarks regarding some of the general lithological characters of lavas may be of service here; the behaviour of the rocks in their emission from volcanic orifices will be described in § 2.

While still flowing or not yet cooled, lavas differ from each other in the extent to which they are impregnated with gases and vapours. Some appear to be saturated, others contain a much smaller gaseous impregnation; and hence arise important distinctions in their behaviour (pp. 296-308). They further differ in viscosity or liquidity, the acid kinds being generally more viscous than the basic, so that the latter, other things being equal, flow farthest and spread out most widely. After solidification, lavas present some noticeable characters, then easily ascertainable. (1) Their average specific gravity may be taken as ranging between 2·37 and 3·22. (2) The heavier (basic) varieties contain much magnetic or titaniferous iron, with augite and olivine, their composition being basic, and their proportion of silica averaging about 45 to 55 per cent. In this group come the basalts, nepheline-lavas, and leucite-lavas. The lighter (acid) varieties contain commonly a minor proportion of metallic bases, but are rich in silica, their percentage of that acid ranging between 70 and 75. Among their more important varieties are the rhyolites and obsidians. Intermediate varieties (trachytes, phonolites, and andesites) connect these two series. (3) Lavas differ much in structure and texture. (*a*) Some are entirely crystalline, consisting of an interlaced mass of crystals and crystalline particles, as in some dolerites and granitoid rhyolites. Even quartz, which used to be considered a non-volcanic mineral, characteristic of the older and chiefly of the plutonic eruptive rocks, has been observed in large crystals in modern lava (liparite and quartz-andesite[2]). (*b*) Some show more or less of a half-glassy or stony (devitrified) matrix, in which the constituent crystals are imbedded; this is the most common arrangement. (*c*) Others are entirely vitreous, such crystals or crystalline particles as occur in them being quite subordinate, and, so to speak, accidental enclosures in the main glassy mass. Obsidian or volcanic glass is the type of this group. (*d*) They further differ in the extent to which minute pores or larger cellular spaces have been developed in them. According to Bischof, the porosity of lavas depends on their degree of liquidity, a porous lava or slag, when reduced in his fusion-experiments to a thin-flowing consistency, hardening into a mass as compact as the densest lava or basalt.[3] But probably a much more effective influence in producing this structure is that of the amount of absorbed vapours and gases. The presence of interstitial steam in lavas, by expanding the still molten stone, produces an open cellular texture, somewhat like that of sponge or of bread. Such a vesicular arrangement very commonly appears on the upper surface of a lava current, which assumes a slaggy or cindery aspect. In some forms of pumice the proportion of air cavities is 8 or 9 times that of the enclosing glass. (4) Lavas vary greatly in colour and general external aspect. The heavy basic

[1] "Alles ist Lava, was im Vulkan fliesst und durch seine Flüssigkeit neue Lagerstätter einnimmt," is Leopold von Buch's comprehensive definition.

[2] Wolf, *Neues Jahrb.* 1874, p. 377.

[3] 'Chem. und Phys. Geol.' supp. (1871), p. 144. On the production of the vesicular structure consult Dana, 'Characteristics of Volcanoes,' p. 161. Compare also Judd, *Geol. Mag.* 1888, p. 7.

kinds are usually dark grey, or almost black, though, on exposure to the weather, they acquire a brown tint from the oxidation and hydration of their iron. Their surface is commonly rough and ragged, until it has been sufficiently decomposed by the atmosphere to crumble into soil which, under favourable circumstances, supports a luxuriant vegetation. The less dense lavas, such as phonolites and trachytes, are frequently paler in colour, sometimes yellow or buff, and decompose into light soils; but the obsidians present rugged black sheets of rock, often roughened with ridges and heaps of grey froth-like pumice. Some of the most brilliant surfaces of colour in any rock-scenery on the globe are to be found among volcanic rocks. The walls of active craters glow with endless hues of red and yellow. The Grand Cañon of the Yellowstone River has been dug out of the most marvellously tinted lavas and tuffs.

4. **Fragmentary Materials.**—Under this title may be included all the substances which, driven up into the air by volcanic explosions, fall in solid form to the ground—the dust, ashes, sand, cinders, and blocks of every kind which are projected from a volcanic orifice.[1] These materials differ in composition, texture, and appearance, even during a single eruption, and still more in successive explosions of the same volcano. For the sake of convenience, separate names are applied to some of the more distinct varieties, of which the following may be enumerated:—

(1) Ashes and dust.—In many eruptions, vast quantities of an exceedingly fine light grey powder are ejected. As this substance greatly resembles what is left after a piece of wood or coal is burnt in an open fire, it has been popularly termed *ash*, and this name has been adopted by geologists. If, however, by the word ash, the result of combustion is implied, its employment to denote any product of volcanic action must be regretted, as apt to convey a wrong impression. The fine ash-like dust ejected by a volcano is merely lava in an extremely fine state of comminution. So minute are the particles that they find their way readily through the finest chinks of a closed room, and settle down upon floor and furniture, as ordinary dust does when a house is shut up. From this finest form of material, gradations may be traced, through what is termed volcanic sand, into the coarser varieties of ejected matter. In composition, the ash and sand vary necessarily with the nature of the lava from which they are derived. Their microscopic structure, and especially their abundant microlites, crystals, and volcanic glass, have been already referred to (pp. 172-175). At first the volcanic particles have the temperature of the molten rock from which they are discharged, and they may reach the ground when still at a red heat. It was a descending cloud of such intensely hot material which, mingled with superheated steam and other vapours, charred and ignited combustible objects during the disastrous eruption at Martinique in May 1902.

In their passage through the air to a distance from the vent of eruption these fine materials undergo a process of sifting, the larger and heavier particles descending first to the ground, while the smallest and lightest are carried farthest. Matteucci has noticed this fact in the proportion of magnetite found in the dust ejected from Vesuvius according to increase of distance from the centre.[2]

(2) Lapilli (p. 172) are ejected fragments of lava, ranging from the size of a pea to that of a walnut; round, subangular, or angular in shape, and having the same indefinite range of composition as the finer dust. As a rule, the larger pieces fall nearest the focus of eruption. Sometimes they are solid, but more usually have a cellular texture, while sometimes they are so light and porous as to float readily on

[1] The student will find a classification and description of the fragmentary material ejected from Vesuvius during the explosive eruption of April-May 1900 in *Boll. Soc. Sism. Ital.* vol. vi.

[2] *Boll. Soc. Sism. Ital.* vol. vi.

water, and, when ejected near the sea, to cover its surface. Well-formed crystals occur in the lapilli of many volcanoes, and are also ejected separately. It has been observed indeed that the fragmentary materials not infrequently contain finer crystals than the accompanying lava.[1] Lapilli may be largely derived from the disruption of more or less cooled and consolidated lava in the volcanic chimney, such as the crust of congealed rock upon the crater floor.

(3) Scoriæ.—the rugged clinker-like lumps that form on the surface of molten lava when exposed to the air and distended by the expansion of its imprisoned vapour. These masses are sometimes ejected in great numbers from the lava in the chimney of a volcanic vent, partly falling back into the crater and partly down the outside of the cone. The term "slag"[2] (from the waste products of iron furnaces and glass-works) is often applied to one of these rough, irregular, porous fragments.

(4) Volcanic Bombs.—These have originally formed portions of the column of molten lava ascending the pipe of a volcano, and have been detached and hurled into the air by successive explosions of steam. They are round, elliptical, or pear-shaped,

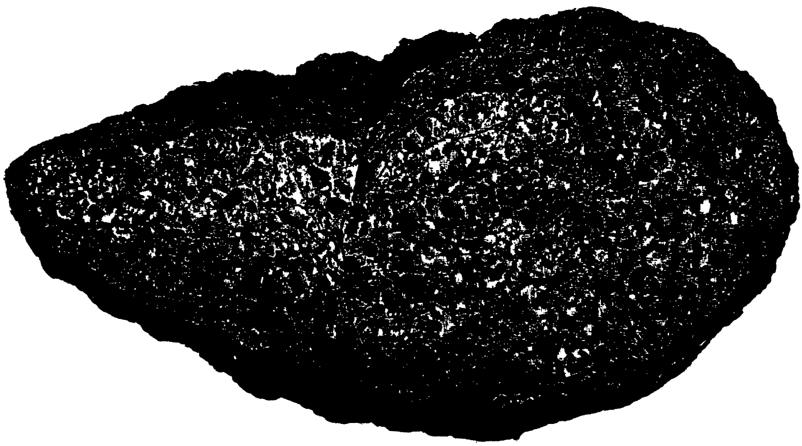

Fig. 40.—Section of Volcanic Bomb, one-third natural size.

often discoidal, from a few inches to several feet in diameter; sometimes tolerably solid throughout, more usually coarsely cellular or pumiceous inside (Fig. 40). Not infrequently the interior is hollow, and the bomb then consists of a shell which is most close-grained towards the outside, or the centre is a block of stone with an external coating of lava. One class of the bombs from Etna contains a nucleus of quartzose sandstone broken off from strata within the crust, impregnated with vitreous material and crusted over with a coating of black scoriaceous olivine-bearing pyroxenic lava.[3] The bombs from the last eruption of the island of Vulcano were ellipsoidal pieces of pumice, with an outer and inner vesicular glassy skin about half an inch thick, which from its cracks and cellular condition has suggested the appellation, "bread-crust structure."[4] Some of these bombs were of great size, ranging from

[1] Sartorius von Waltershausen, 'Sicilien und Island,' 1853, p. 328.

[2] On the ratio between the pores and volume of the rock in slags and lavas, see determinations by Bischof, 'Chem. und Phys. Geol.' supp. (1871), p. 158.

[3] The types of bombs discharged by Etna are described by Messrs. Duparc and Mrazec, *Arch. Sci. Phys. Nat.*, Geneva, xxix. (1893), p. 256.

[4] Dr. Johnston-Lavis, *Proc. Geol. Assoc.* xi. (1890), p. 390. The Vesuvian bombs are described by Matteucci, *Boll. Soc. Sism. Ital.* vi. p. 45 of reprint.

one to six metres in diameter, one actually reaching the dimensions 6 × 5 × 1 metres, and thus containing about 25 cubic metres and weighing nearly 68 tons.[1] There can be no doubt that, when torn by eructations of steam from the surface of the boiling lava, the material of the bombs is in a thoroughly molten condition. From the rotatory motion imparted by its ejection, it takes a circular form, and in proportion to its rapidity of rotation and fluidity is the amount of its "flattening at the poles." The centrifugal force within allows the expansion of the interstitial vapour, while the outer surface rapidly cools and solidifies; hence the more close-grained crust, and the more porous or cavernous interior. Bombs, varying from the size of an apple to that of a man's body, were found by Darwin abundantly strewn over the ground in the island of Ascension; they were also ejected in vast quantities during the eruption of Santorin in 1866.[2] Among the tuffs of the Eifel region, small bombs, consisting mostly of granular olivine, are of common occurrence, as also pieces of sanidine or other less fusible minerals which have segregated out of the magma before ejection. In like manner, among the tuffs filling volcanic necks, probably of Permian age, which pierce the Carboniferous rocks of Fife, large worn crystals of orthoclase, biotite, &c., are found.[3]

(5) Volcanic Blocks are larger pieces of stone, often angular in shape. In some cases they appear to be fragments loosened from already solidified rocks in the chimney of the volcano. Hence we find among them pieces of non-volcanic rocks, as well as of older tuffs and lavas recognisably belonging to early eruptions. In many cases, they are ejected in enormous quantities during the early phases of violent eruption. The great explosion from the side of Ararat in 1840 was accompanied by the discharge of a vast quantity of fragments over a space of many square miles around the mountain. Whitney has described the occurrence in California of beds of such fragmentary volcanic breccia, hundreds of feet thick and covering many square miles of surface. Junghuhn, in his account of the eruption in Java in 1772, mentions that a valley ten miles long was filled to an average depth of fifty feet with angular volcanic débris.[4]

Among the earlier eruptions of a volcano, fragments of the rocks through which the vent has been drilled may frequently be observed. These are in many cases not volcanic. Blocks of schist and granitoid rocks occur in the cinder-beds at the base of the volcanic series of Santorin. In the older tuffs of Somma, pieces of altered limestone (sometimes measuring 200 cubic feet or more and weighing upwards of 15 tons) are abundant, and often contain cavities lined with the characteristic "Vesuvian minerals."[5] Blocks of a coarsely crystalline granitoid (but really trachytic) lava have been particularly observed both on Etna[6] and Vesuvius. In the year 1870 a mass of that kind, weighing several tons, was to be seen lying at the foot of the upper cone of Vesuvius, within the entrance to the Atrio del Cavallo. During the eruption of this volcano in the spring of 1900 an immense quantity of blocks was ejected, the largest of them estimated to contain 12 cubic metres and to weigh 30,000 kilograms.[7] Similar blocks occur among the Carboniferous and later volcanic pipes of Central Scotland, together sometimes with huge fragments of sandstone, shale, or limestone, not infrequently full of Carboniferous fossils.[8] Enormous masses of various schists have been carried up by the lavas of the Tertiary volcanic plateau of the Inner Hebrides.[9]

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[1] Bergeat, 'Die Aeolischen Inseln,' p. 186.

[2] Darwin, 'Geological Observations on Volcanic Islands,' 2nd edit. p. 42. Fouqué, 'Santorin,' p. 79.

[3] 'Geology of East Fife,' *Mem. Geol. Surv.* 1902, p. 271.

[4] See remarks on volcanic conglomerates, *ante*, p. 173. By the eruptions of May 1902 the valleys of St. Vincent were deeply filled with red-hot sand (p. 286).

[5] Johnston-Lavis, *Q. J. G. S.* xl. p. 75; *Trans. Edin. Geol. Soc.* vi. (1893), pp. 314-351.

[6] For the erupted blocks (Auswürflinge) of Etna, see 'Der Aetna,' ii. pp. 216, 330, 461.

[7] Matteucci, *Boll. Soc. Sism. Ital,* vi. p. 57.

[8] *Trans. Roy. Soc. Edin.* xxix. p. 459. See *postea*, Book IV. Sect. vii. § 1 4.

[9] *Trans. Roy. Soc. Edin.* xxxv. (1888), p. 82.

The fragmentary materials erupted by a volcano and deposited around it acquire by degrees more or less consolidation, partly from the mere pressure of the higher upon the lower strata, partly from the influence of infiltrating water. It has been already stated (p. 172) that different names are applied to the rocks thus formed. The coarse, tumultuous, unstratified accumulation of volcanic débris within a crater or funnel is called Agglomerate. When the débris, though still coarse, is more rounded, and is arranged in a stratified form, especially where it is re-assorted by moving water, as by rain, streams, lakes, or the sea, it becomes a Volcanic Conglomerate. The finer-grained varieties, formed of dust and lapilli, are included in the general designation of Tuffs. These are usually pale yellowish, greyish, or brownish, sometimes black rocks, granular, porous, and often incoherent in texture. They occur interstratified with and pass into ordinary non-volcanic sediment.

Organic remains sometimes occur in tuff. Where volcanic débris has accumulated over the floor of a lake, or of the sea, the entombing and preserving of shells and other organic objects must continually take place. Examples of this kind are cited in later pages of this volume from older geological formations. Professor Guiscardi of Naples found about 100 species of marine shells of living species in the old tuffs of Vesuvius. Marine shells have been picked up within the crater of Monte Nuovo, and have been frequently observed in the old or marine tuff of that district. Showers of ash, or sheets of volcanic mud, often preserve land-shells, insects, and vegetation living on the area at the time. The older tuffs of Vesuvius have yielded many remains of the shrubs and trees which at successive periods have clothed the flanks of the mountain. Fragments of coniferous and lepidodendroid wood, which probably once grew on the slopes or within the craters of the tuff-cones in Central Scotland, are abundant in the "necks" of that region. The minute structure of some of these plants has been admirably preserved in the beds of tuff intercalated among the Carboniferous formations.[1]

## § 2. Volcanic Action.

Volcanic action may be either constant or periodic. Stromboli, in the Mediterranean, so far as we know, has been uninterruptedly emitting hot stones and steam, from a basin of molten lava, since the earliest period of history.[2] This activity though constant is variable. Thus in the ten years between 1879 and 1888 the usual moderate energy was interrupted fourteen times by more or less violent paroxysms. In its ordinary condition this volcano ejects ashes and stones at frequent intervals with greater or less violence, and sometimes with the emission of lava. A diary was kept of its doings on 7th July 1891, when from two of its eruptive vents, at intervals varying from less than a minute up to about half an hour, there were about thirty explosions between half-past eight

[1] *Trans. Roy. Soc. Edin.* xxix. p. 470; 'Geology of Eastern Fife,' *Mem. Geol. Surv.* 1902, p. 274; and *postea*, Book IV. Part VII. Sect. ii. § 2.

[2] For accounts of THE LIPARI ISLANDS see Spallanzani's 'Voyages dans les deux Siciles.' Scrope's 'Volcanoes.' Judd, *Geol. Mag.* 1875. Mercalli's 'Vulcani, &c.' p. 135; his papers in *Atti Soc. Ital. Sci. Nat.* xxii. xxiv. xxvii. xxix. xxxi., and those cited *postea*. A. Baltzer, *Z. D. G. G.* xxvi. (1875). L. W. Fulcher, *Geol. Mag.* 1890, p. 347. "Le Eruzioni dell' Isola di Vulcano, 3 agosto 1888—22 marzo 1890," *Ann. Uff. Centr. Meteorol. e Geodinamica*, x. part iv. (1888). E. Cortese and V. Sabatini, 'Descrizione Geologico-petrografica delle Isole Eolie,' Rome, 1892; A. Bergeat, "Die Aeolischen Inseln," *Abhand. Bayer. Akad.*, Munich, ii. Cl. vol. xx. Abth. i. (1899). A good bibliography of the Lipari Islands up to 1890 will be found in Dr. Johnston-Lavis, 'South Italian Volcanoes,' cited on p. 263.

o'clock in the morning and a few minutes past two in the afternoon, or on the average from six to seven in the hour. Some of the explosions were extremely weak, but some were vigorous enough to eject red-hot stones, the incandescence of which could be seen at a distance, in spite of the daylight, while occasionally the ground sensibly trembled.[1]

Among the Moluccas, the volcano Sioa, and in the Friendly Islands, that of Tofua, have never ceased to be in eruption since their first discovery. The lofty cone of Sangay, among the Andes of Quito, is always giving off hot vapours; Cotopaxi is ever constantly active,[2] as is also Izalco in San Salvador, Central America. But, though examples of unceasing action may thus be cited from widely different quarters of the globe, they are nevertheless exceptional. The general rule is that a volcano breaks out from time to time with varying vigour, and after longer or shorter intervals of quiescence.

**Active, Dormant, and Extinct Phases.**—It is usual to class volcanoes as *active*, *dormant*, and *extinct*. This arrangement, however, often presents considerable difficulty in its application. An active volcano cannot of course be mistaken, for even when not in vigorous eruption it shows by its discharge of steam and hot vapours that it might break out again at any moment. But in many cases it is impossible to decide whether a volcano should be called extinct or only dormant. The volcanoes of Silurian age in Wales, of Carboniferous age in Ireland, of Permian age in the Harz, of Miocene age in the Hebrides, of younger Tertiary age in the Western States and Territories of North America, are certainly all extinct. But the older Tertiary volcanoes of Iceland are still represented there by Skaptar-Jökull, Hecla, and their neighbours.[3] Somma, in the first century of the Christian era, would have been naturally regarded as an extinct volcano. Its fires had never been known to have been kindled; its vast crater was a wilderness of wild vines and brushwood, haunted, no doubt, by wolf and wild boar. Yet in a few days, during the autumn of

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[1] Professors Riccò and Mercalli have given a detailed account of the eruptive movement in Stromboli, *Ann. Uff. Centr. Meteorol.* xi. part iii. (1892). Another diary of five hours was kept on 11th October 1894, by Dr. Bergeat, with somewhat similar results: 'Die Aeolischen Inseln,' p. 36.

[2] For descriptions of Cotopaxi, see Wolf, *Neues Jahrb.* 1878; Whymper, *Nature*, xxiii. p. 323; 'Travels amongst the Great Andes,' chap. vi.

[3] On the volcanic phenomena of ICELAND, consult G. Mackenzie's 'Travels in the Island of Iceland during the Summer of 1810.' E. Henderson's 'Iceland.' Zirkel, 'De geognostica Islandae constitutione observationes,' Bonn, 1861. Thoroddsen, 'Oversigt over de Islandske Vulkaners Historie,' translated in *résumé* by G. H. Boehmer, *Smithsonian Inst. Rep.* 1885, part i. p. 495; also *Bihang t. Svensk. Vet. Akad. Handl.* xiv. ii. (1888), xvii. ii. (1891); *Geol. Mag.* 1880, p. 458; *Nature*, Oct. 1884. *Geograph. Tidsk.* vol. x. (1889-1890), pp. 149-172; xii. (1893-94), pp. 167-234; xiii. (1895), pp. 3-37, 99-122, 140-156; xiv. (1897-98), pts. 1, 2, 5, 6; xv. (1899), pp. 3-14; xvi. (1901-1902), pp. 58-80. *Verhandl. Gesel. Erdk.*, Berlin, 1895, p. 187. *Mitth. K. K. Geogr. Ges.*, Vienna, xxiv. (1891), p. 117. Keilhack, *Z. D. G. G.* xxxviii. (1886), p. 376; Schmidt, *op. cit.* xxxvii. (1885), p. 737. A. Helland, "Lakis Kratere og Lava-strøme," *Universitets Programme*, Christiania, 1885. Bréon, 'Géologie de l'Islande, et des Isles Faeroe,' Paris, 1884. T. Anderson, *Journ. Soc. Arts*, vol. xl. (1892), p. 397.

the year 79, the half of the crater walls was blown out by a terrific series of explosions, the present Vesuvius was then formed within the limits of the earlier crater, and since that time volcanic action has been intermittently exhibited up to the present day. Some of the intervals of quietude, however, have been so considerable that the mountain might then again have been claimed as an extinct volcano. Thus, in the 131 years between 1500 and 1631, so completely had eruptions ceased that the crater had once more become choked with copsewood. A few pools and springs of very salt and hot water remained as memorials of the former condition of the mountain. But this period of quiescence closed with the eruption of 1631,—the most powerful of all the known explosions of Vesuvius, except the great one of 79. Since the middle of the seventeenth century the volcano has been intermittently active but never dormant. Three phases of its energy are recognised. Of these the weakest, known as the Solfataric, is manifested by the constant emission of steam and vapours with the formation of sublimates in the cracks up which these emanations reach the surface. The second, known as the Strombolian, is shown by a continual eructation of dust and stones, which, however, are not ejected with much force, and for the most part fall back into the crater or on the upper part of the cone. In the third and most vigorous phase, which has been termed Plinian, after the historian of the eruption in 79, large volumes of steam, dust, ashes, scoriæ, bombs and blocks are expelled with great violence high into the air and fall around the crater, while occasionally streams of lava issue from rents in the cone and flow down the outside of the mountain.[1]

In the island of Ischia, Mont' Epomeo was last in eruption in the year 1302, its previous outburst having taken place, it is believed, about seventeen centuries before that date. From the craters of the Eifel, Auvergne, the Vivarais, and Central Italy, though many of them look as if they had only recently been formed, no eruption has been known to come during the times of human history or tradition. In the west of North America, from Arizona to Oregon, numerous stupendous volcanic cones occur, but even from the most perfect and fresh of them nothing but steam and hot vapours has yet been known to proceed.[2] But the presence there of hot springs and geysers proves the continued existence of one phase of volcanic action.

In short, no essential distinction can be drawn between dormant and extinct volcanoes. Volcanic action, as will be afterwards pointed out, is apt to show itself again and again, even at vast intervals, within the same regions and over the same sites. As above stated, the dormant or waning condition of a volcano, when only steam and various gases and sublimates are given off, is called the Solfataric phase.

**Sites of Volcanic Action.**—It has been a prevalent belief among

[1] R. V. Matteucci, *Tschermak's Mitth.* xv. (1895), part v.; *Bol. Soc. Sism. Ital.* vi. p. 32 of reprint.

[2] Eruptions occurred perhaps less than 100 years ago. Diller, *Bull. U. S. G. S.* No. 79. I. C. Russell's 'Volcanoes of North America' gives a valuable summary of information regarding the later volcanic history of the United States.

geologists that for the appearance of a volcano on the surface of the earth there must first be a fissure of the terrestrial crust, and that the site of the volcano will be generally determined by the weakest point along the line of fracture, where least resistance is offered to the expansive energy of the subterranean vapours. It is undoubtedly true that many groups of volcanoes are placed in lines strongly suggestive of the existence of such fissures in the crust. It is impossible, for example, to study the volcanic map of the globe without concluding that along such lines as the Aleutian and Kurile islands, Japan, and the islands of the East and West Indies there must be long rents underneath, which have provided a pathway for the manifestations of volcanic energy. These major lines of distribution have been cited as a proof of the usual connection between volcanic distribution and fractures in the crust.[1]

Nevertheless, that a new volcanic cone may arise without the appearance of any fissure has been shown by instances that have been witnessed both in the Old and New Worlds. Thus on the shores of the Bay of Naples, among gardens and cottages, Monte Nuovo, to which further reference will be made in the sequel, was piled up within a space of two days to a height of nearly 500 feet. Again, in the year 1770 a new volcano (Izalco) broke out in the midst of a cattle estate about 30 miles west of the city of San Salvador. Since that time it has been constantly active, and has now attained a height of about 3000 feet. In the same volcanic region, early in 1880, a volcano burst forth in the lake Hopango, and speedily formed an island about 5 acres in extent and 160 feet high, though the water immediately around it was 100 fathoms in depth. Further, in the volcanic ground of Nicaragua during 1850, a volcanic cone was thrown up at the edge of the plain of Leon. It is true that all these eruptions took place in tracts that had already been theatres of volcanic activity, and where there are still active volcanoes. But they indicate that new vents may be opened to the surface at some little distance from any older funnels and without the accompaniment of any visible fissure.

For some years past there has been a growing belief that while linear groups of volcanoes no doubt indicate the existence of rents or lines of weakness in the terrestrial crust, volcanic energy is of itself capable of drilling an orifice through the crust and forcing its way to the surface. The absence of any contributory fissure can be demonstrated in the case of many ancient volcanic vents, the ground-plan and surroundings of which have been laid bare by denudation. Thus as far back as the year 1879 I observed that the numerous volcanic vents of Carboniferous and later age in Central Scotland have been blown out of the crust without any trace of their coincidence with lines of fault.[2] In 1886 Dr. Ferdinand Löwe combated the prevailing conception,

[1] See, for instance, M. Michel-Lévy's essay, "Sur la Co-ordination et la Répartition des Fractures et des Effondrements de l'Écorce terrestre en relation avec les Épanchements volcaniques," *Bull. S. G. F.* xxvi. (1898), p. 105.

[2] *Trans. Roy. Soc. Edin.* xxix. (1879). The independence of faults on the part of these vents was noticed in the first edition of this text-book, published in 1882, p. 559.

maintaining that the magma had of itself energy sufficient to enable it to perforate the crust without the help of a fissure.[1] Professor Branco has been led to a similar conclusion from his study of the numerous volcanic necks of Swabia, which in many respects repeat the structure of the older series in Scotland. Dr. E. Boese, of the Geological Institute of Mexico, has more recently adopted the same view, which he says is borne out by a study of the volcanoes of that country.[2] This subject will again be referred to in § 5, and in Book IV. Part VII. Sect. i. § 4. In the meantime it may be sufficient to note that while the subterranean energy of the planet doubtless avails itself of any lines or points of weakness in the crust, the existence of lines of fissure is not absolutely essential for the production of volcanoes, and that many ancient volcanic vents, the surroundings of which have been entirely laid bare by denudation, can be demonstrated to have risen without the help of any visible faults.[3]

An important inference may be deduced from the considerations just stated. It is obvious that in order to be able to expel an overlying column of the earth's crust the magma must have ascended to within a comparatively short distance from the surface. In the case of the innumerable small vents which can be proved to have been drilled through unfaulted rocks, this proximity of the top of the magma to the mouths of the funnels becomes strikingly apparent. And as these vents are numerous they show that in many cases volcanic action is not deep-seated but has its source not many hundred feet below ground. The ascertained relation between the eruptive activity of some volcanoes, such as Stromboli and Vesuvius, and seasons of wet weather (p. 281), together with the briefness of the interval of time between the fall of the rain and the renewal of volcanic explosions, points to the comparatively superficial character of some manifestations of volcanic phenomena.[4]

Volcanoes may break through any geological formation. In Auvergne,[5] in the Miocene period, they burst through the granitic and gneissose plateau of Central France. In Lower Old Red Sandstone times, they pierced contorted Silurian rocks in Central Scotland. In late Tertiary

[1] *Jahrb. K. K. Geol. Reichsanst.* 1886, p. 315.

[2] Branco, 'Schwabens 125 Vulkan-Embryonen,' Stuttgart, 1894 ; *Neues Jahrb.* i. (1898), p. 175 ; E. Boese, *Mem. Soc. Alzate, Mexico*, xiv. (1899), p. 199.

[3] 'Ancient Volcanoes of Great Britain,' i. p. 69 ; ii. p. 65.

[4] See Stübel's 'Vulkanberge von Ecuador,' 1897 ; and 'Ein Wort über den Sitz der vulkanischen Kräfte in der Gegenwart,' Leipzig, 1901. G. de Lorenzo, "Considerazioni sull' Origine superficiale dei Vulcani," *Atti Acad. Sci.*, Naples, xi. (1902) ; *Rend. Acad. Sci.*, Naples, Nov. 1901.

[5] For descriptions of AUVERGNE and the volcanic districts of Central France, see Scrope's 'Geology and Extinct Volcanoes of Central France,' 2nd edit. 1858. H. Lecoq's 'Époques géologiques de l'Auvergne,' 1867. Michel-Lévy, *B. S. G. F.* xviii. (1890), p. 688. The succession of volcanic rocks in Velay is described by M. Boule, *B. S. G. F.* xviii. (1889), p. 174, and in *Bull. Carte Géol. de la France*, No. 28 (1892) ; see also P. Termier, *op. cit.* No. 13 ; J. Giraud, *op. cit.* No. 87 ; P. Glangeaud, *Compt. rend.* 5th June 1900. An interesting historical sketch of the progress of investigation in Auvergne will be found in a pamphlet by Antoine Vernière, "Les Voyageurs et les Naturalistes dans l'Auvergne et dans le Velay," Clermont Ferrand, 1900.

and post-Tertiary ages, they found their way through recent soft marine strata, and formed the huge piles of Etna, Somma, and Vesuvius; while in North America, during the same cycle of geological time, they flooded with lava and tuff many of the river-courses, valleys, and lakes of Nevada, Utah, Wyoming, Idaho, and adjacent territories. On the banks of the Rhine, at Bonn and elsewhere, they have penetrated some of the older alluvia of that river. In many instances, also, newer volcanoes have appeared on the sites of older ones. In Scotland, the Carboniferous volcanoes have risen on the ruins of those of the Old Red Sandstone, those of the Permian period have broken out among the earlier Carboniferous eruptions, while the older Tertiary dykes have been injected into all these older volcanic masses. The newer *puys* of Auvergne were in some cases erupted through much older and already greatly denuded basalt-streams. Somma and Vesuvius have risen out of the great Neapolitan plain of older marine tuff, while in Central Italy newer cones have been thrown up upon the wide Roman plain of more ancient volcanic débris.[1] The vast Snake River lava-fields of Idaho overlie denuded masses of earlier trachytic lavas, and similar proofs of a long succession of intermittent and widely separated volcanic outbursts can be traced northwards into the Yellowstone basin.

**Ordinary phase of an Active Volcano.**—The interval between two eruptions of an active volcano shows a gradual augmentation of energy. The crater, emptied by the last discharge, has its floor slowly upraised by the expansive force of the lava-column underneath. Vapours rise in constant outflow, accompanied sometimes by discharges of dust or stones. Through rents in the crater floor red-hot lava may be seen only a few feet down. Where the lava is maintained at or above its fusion-point and possesses great liquidity, it may form boiling lakes, as in the great crater of Kilauea, where acres of seething lava may be watched throwing up fountains of molten rock, surging against the walls and re-fusing large masses that fall into the burning flood. The lava-column inside the pipe of a volcano is all this time gradually rising, until some weak part of the wall allows it to escape, or until the pressure of the accumulated vapours becomes great enough to burst through the hardened crust of the crater-floor and give rise to the phenomena of an eruption.

**Influence of Atmosphere.**—Leaving for the present the general question of the cause of volcanic action, it may be here remarked that the conditions determining any particular eruption are still unknown. The explosions of a volcano may be to some, probably slight, extent regulated by the conditions of atmospheric pressure over the area at the time. When we remember the connection, now indubitably established, between a more copious discharge of fire-damp in mines and a lowering of atmospheric pressure, a similar influence may well affect the escape of vapours from the upper surface of a lava-column; for it is mainly to the expansive vapours impregnating the lava that the manifesta-

[1] According to Professor G. Pozzi, the principal volcanic outbursts of Italy are of the Glacial period: *Atti Lincei*, ii. (1878), p. 35. G. de Stefani regards those of Tuscany as partly Miocene, partly Pliocene and post-Pliocene: *Proc. Tosc. Soc. Nat. Pisa*, 1. p. xxi.

tions of volcanic activity are due. In the case of a volcanic funnel like Stromboli, where, as Scrope pointed out, the expansive subterranean force within, and the repressive effect of atmospheric pressure without, just balance each other, any serious disturbance of that pressure might be expected to make itself evident by a change in the condition of the volcano. Accordingly, it has long been remarked by the fishermen of the Lipari Islands that in stormy weather there is at Stromboli a more copious discharge of steam and stones than in fine weather. They make use of the cone as a weather-glass, the increase of its activity indicating a falling, and the diminution a rising barometer.[1] There may, however, be other causes besides atmospheric pressure concerned in these differences; the preponderance of rain during the winter and spring may be one of these.

During the eruption of Vulcano, which lasted from the beginning of August 1888 to near the end of March 1890, the Government Commission to the island kept a meteorological record for the purpose of ascertaining what connection there might be between the explosions and the state of the atmosphere. The length of time during which the observations were carried on was probably too brief to warrant any very definite conclusion on the subject; but so far as the observations went they indicated that while the main cause of variation in the volcanic energy was to be sought in subterranean conditions, there yet appeared to be on the whole a coincidence between the feebler manifestations of volcanic activity and a high barometer, while the more vigorous displays corresponded to changes from settled to stormy weather.[2]

At Hawaii evidence of a relation of volcanic activity to the seasons has been established beyond question. Out of the whole number of eruptions from Mauna Loa, 19 in number, from 1832 to 1887, 5 occurred in January, 3 in February, 4 in March April and May, 1 in June; 4 began in August and 2 in November. Thus 15 out of the 19 took place in the wetter season. If to these are added the eruptions at Kilauea, the numbers become 20 or 21 out of a total of 27.[3] Again, Etna, according to Sartorius von Waltershausen, is most active in the winter months; while among the Vesuvian eruptions since the middle of the seventeenth century, the number which took place in winter and spring has been to that of those which broke out in summer and autumn as

[1] A. Bergeat, "Der Stromboli als Wetterprophet," *Z. D. G. G.* xlviii. (1896), pp. 153-239.

[2] Silvestri and Mercalli, 'Le Eruzioni dell' Isola di Vulcano,' p. 113.

[3] This seasonal relation was first noticed by the Rev. T. Coan, and was recognised by Mr. W. Lowthian Green, J. D. Dana, *Amer. Journ. Sci.* xxxvi. (1888), p. 84. For accounts of the volcanic phenomena of HAWAII, see W. Ellis, 'Polynesian Researches.' Wilkes' *U.S. Exploring Expedition*, 1838-42, "Geology," by J. D. Dana. Mr. Coan, a missionary resident in Hawaii, observed the operations of the volcanoes for upwards of forty years, and published from time to time short notices of them in the *American Journal of Science*, vols. xiii. (1852) xiv. xv. xviii. xxi. xxii. xxiii. xxv. xxvii. xxxvii. xl. xliii. xlvii. xlix.; 3rd ser. ii. (1871) iv. vii. viii. xiv. xviii. xx. xxi. xxii. (1881). Professor Dana revisited these volcanoes and fully discussed their phenomena in the *Amer. Journ. Sci.* vols. xxxiii.-xxxvii. (1887-89), and in his 'Characteristics of Volcanoes.' See also C. E. Dutton, *Amer. Journ. Sci.* xxv. (1883), p. 219; *Report U.S. Geological Survey*, 1882-83. L. Green, 'Vestiges of the Molten Globe,' 1887. W. T. Brigham, *Amer. Journ. Sci.* xli. (1891), p. 507; S. E. Bishop, *op. cit.* xliv. (1892), p. 207; xlv. (1893), p. 241; xlviii. (1894), p. 338; E. Wood, *Amer. Geol.* xxiv. (1899), p. 300; C. H. Hitchcock, *B. Amer. Geol. Soc.* xi. (1901), pp. 36-49; xii. (1901), p. 45; *Nature*, xlvii. (1893), p. 499; l. (1894), pp. 91, 483; liii. (1896), p. 490. For an account of the remarkable glassy lavas of Hawaii, see E. Cohen, *Neues Jahrb.* 1880 (ii.), p. 23; and a general account of the petrography of the islands, by E. S. Dana, *Amer. Journ. Sci.* xxxvii. (1889), p. 441.

7 to 4. The influence of a rainy season in augmenting the activity of Vesuvius has recently been repeatedly urged by G. de Lorenzo. He has pointed out that the recrudescence of Strombolian explosive energy in this mountain during May 1900 followed after an exceptionally rainy season, and that a similar effect re-appeared after the heavy rains of the following November and February.[1] In Japan the greater number of recorded eruptions have taken place during the cold months of the year, February to April.[2]

According to Mr. Coan, previous to the great Hawaiian eruption of 1868 there had been unusually wet weather, and to this fact he attributes the exceptional severity of the earthquakes and volcanic explosions. The greater frequency of Japanese volcanic eruptions and earthquakes in winter has been referred in explanation to the fact that the average barometric gradient across Japan is steeper in winter than in summer, while the piling up of snow in the northern regions gives rise to long-continued stresses, in consequence of which certain lines of weakness in the earth's crust are more prepared to give way during the winter months than they are in summer.[3] The effects of varying atmospheric pressure, however, probably at most only slightly and locally modify volcanic activity. Eruptions, like the great one of Cotopaxi in 1877, have in innumerable instances taken place without, so far as can be ascertained, any reference to atmospheric conditions.

Kluge has sought to trace a connection between the years of maximum and minimum sun-spots and those of greatest and feeblest volcanic activity, and has constructed lists to show that years which have been specially characterised by terrestrial eruptions have coincided with those marked by few sun-spots and diminished magnetic disturbance.[4] Such a connection cannot be regarded as having yet been satisfactorily established. Again, the same author has called attention to the frequency and vigour of volcanic explosions at or near the time of the August meteoric shower. But the cited examples can hardly yet be looked upon as more than coincidences.

**Periodicity of Eruptions.**—At many volcanic vents the eruptive energy manifests itself with more or less regularity. At Stromboli, which is constantly in an active state, the explosions occur, as we have seen, at intervals varying from less than a minute up to half an hour or more. A similar rhythmical movement has been often observed during the eruptions at other vents which are not constantly active. Vulcano, for example, during its eruption of September 1873, displayed a succession of explosions which followed each other at intervals of from twenty to thirty minutes. The same volcano repeated its alternations of gentle and violent discharges during the eruptive period above referred to

[1] *Rend. Accad. Sci.*, Naples, Fasc. 5 and 6, 8 to 12, 1900; Fasc. 3, 1901.

[2] J. Milne, *Seismol. Soc. Japan*, ix. part ii. p. 174. For accounts of the volcanic phenomena of JAPAN, the *Transactions of the Seismological Society of Japan* should be consulted. See also Dr. B. Kotô, 'Scope of the Vulcanological Survey of Japan,' Tokio, 1900, where a list of papers on the Japanese volcanoes, published and in preparation, will be found; E. Naumann, "Die Vulcaninsel Ooshima," *Z. D. G. G.* xxix. (1877), pp. 364-391; S. Sekiya and Y. Kikuchi, 'The Eruption of Bandaisan,' Tokio, 1889; W. J. Holland, "Ascent of the Volcanoes Nantai-san, Asama-yama, and Nasu-take," *Appalachia*, Boston, Dec. 1890.

[3] J. Milne, *loc. cit.*

[4] 'Ueber Synchronismus und Antagonismus,' 8vo, Leipzig, 1863, p. 72. A. Poëy (*Comptes rend.* lxxviii. (1874), p. 51) believes that among the 786 eruptions recorded by Kluge, between 1749 and 1861, the maxima correspond to periods of minimum in solar spots. Compare the reported connection of earthquakes with sun-spots, &c., *postea*, p. 363.

as having lasted from August 1888 to March 1890. A diary of the explosions was kept for each day between the 11th February and 24th March 1889. During that interval three periods could be distinguished that differed in the rhythm and intensity of the eruptions. The first of these, from 11th to 23rd February, was characterised by the great frequency and moderate intensity of the explosions, having on the average twelve explosions in the hour, with intervals always less than 20 minutes, except in one case, where the intervals reached 29 minutes. The second period, from 24th February to 20th March, was marked by the diminished frequency and greater intensity of the eruptions, the average being seven in the hour, with intervals between them generally less than half an hour, but in one case 48 minutes and in another 1 hour and 12 minutes. In the third period, from the 22nd to the 24th of March, the eruptions were few in number and moderate in intensity, with intervals between them of even 3 hours and more.[1]

At Etna and Vesuvius a similar rhythmical series of convulsive efforts has often been observed during the course of an eruption.[2] Among the volcanoes of the Andes a periodic discharge of steam has been observed; Mr. Whymper noticed outrushes of steam to proceed at intervals of from twenty to thirty minutes from the summit of Sangai, while during his inspection of the great crater of Cotopaxi this volcano was seen to blow off steam at intervals of about half an hour.[3] At the eruption of the Japanese volcano Oshima, in 1877, Mr. Milne observed that the explosions occurred nearly every two seconds, with occasional pauses of 15 or 20 seconds.[4] Kilauea, in Hawaii, seems to show a regular system of grand eruptive periods. Dana has pointed out that since 1832 outbreaks of lava have taken place from that volcano at intervals of from three and a half to twelve and a half years, these intervals being required to fill the crater up to the point of outbreak, or to a depth of 400 or 500 feet.[5]

Some volcanoes have exhibited a remarkable paroxysmal phase of activity, when after comparative or complete quiescence a sudden gigantic explosion has taken place, followed by renewed and prolonged repose. Vesuvius supplies the most familiar illustration of this character of volcanic energy. The great eruption of A.D. 79, which truncated the upper part of the old cone of Somma, was a true paroxysmal explosion, unlike anything that had preceded it within historic times, and far more violent than any subsequent manifestation of the same volcano. This phase of volcanic activity is discussed at p. 289.

**General sequence of events in an Eruption.**—The approach of an

[1] Professor Mercalli, 'Le Eruzioni dell' Isola di Vulcano,' cap. ii. art. 4, p. 75. The observations were continued by Professor O. Silvestri from 25th March 1889 to 22nd March 1890, but not in the same detail.

[2] G. Mercalli, *Atti Soc. Ital. Sci. Nat.* xxiv. (1881).

[3] 'Travels among the Great Andes of the Equator,' 1892, pp. 74, 153.

[4] *Trans. Seism. Soc. Japan*, ix. part ii. p. 82.

[5] 'Characteristics of Volcanoes,' p. 124. *Amer. Journ. Sci.* xxxvi. (1888), p. 83. On periodicity of eruptions, see Kluge, *Neues Jahrb.* 1862, p. 582.

eruption is not always indicated by any premonitory symptoms, for many tremendous explosions are recorded to have taken place in different parts of the world without perceptible warning. Much in this respect would appear to depend upon the condition of liquidity of the lava, and the amount of resistance offered by it to the passage of the escaping vapours through its mass. In Hawaii, where the lavas are remarkably liquid, vast outpourings of them have taken place quietly without earthquakes during the present century. But even there, the great eruption of 1868 was accompanied by violent earthquakes.

The eruptions of Vesuvius are often preceded by failure or diminution of wells and springs. But more frequent indications of an approaching outburst are conveyed by sympathetic movements of the ground. Subterranean rumblings and groanings are heard; slight tremors succeed, increasing in frequency and violence till they become distinct earthquake shocks. The vapours from the crater grow more abundant, as the lava-column in the pipe or funnel of the volcano ascends, forced upward and kept in perpetual agitation by the passage of elastic vapours through its mass. After a long previous interval of quiescence, there may be much solidified lava towards the top of the funnel, which will restrain the ascent of the still molten portion underneath. A vast pressure is thus exercised on the sides of the cone, which, if too weak to resist, will open in one or more rents, and the liquid lava will issue from the outer slope of the mountain; or the energies of the volcano will be directed towards clearing the obstruction in the chief throat, until with tremendous explosions, and the rise of a vast cloud of steam, dust and fragments, the bottom or sides of the crater are finally blown out, and the top of the cone may disappear. Lava may now escape from the lowest part of the lip of the crater, while, at the same time, immense numbers of red-hot bombs, scoriæ, and stones are shot up into the air. The lava at first rushes down like one or more rivers of melted iron, but, as it cools, its rate of motion lessens. Clouds of steam rise from its surface, as well as from the central crater. Indeed, every successive paroxysmal convulsion of the mountain is marked, even at a distance, by the rise of huge ball-like (or cauliflower-like) wreaths or clouds of steam (Fig. 39), mixed with dust and stones, forming a column which towers sometimes a couple of miles or more above the summit of the cone. By degrees these eructations diminish in frequency and intensity. The lava ceases to issue, the showers of stones and dust decrease, and after a time, which may vary from hours to days or months, even in the *régime* of the same mountain, the volcano becomes once more tranquil.[1]

Some of the most destructive eruptions have been unaccompanied by the outflow of any lava. Thus in the disastrous explosions of the West Indian islands in May 1902, by which the town of St. Pierre in Martinique, with 30,000 inhabitants, and a wide tract of country in St. Vincent, with

[1] See Schmidt's narrative of the eruption of Vesuvius in May 1855, together with the other narratives of the eruptions of that mountain cited on p. 267, and those of Etna enumerated on p. 264. An account of the great eruption of Cotopaxi in June 1877, by Dr. Th. Wolf, will be found in *Neues Jahrb.* 1878, p. 113.

2000 or more of the population, were destroyed in a few minutes, no lava appears to have been poured forth except in the form of vast quantities of incandescent dust, sand and stones, into which it was blown by the explosion of the vapours and gases occluded in it. At these two volcanoes "the most peculiar feature of the eruptions was the avalanche of incandescent sand and the great black cloud which accompanied it. The preliminary stages of such eruptions, which may occupy a few days or only a few hours, consist of outbursts of steam, fine dust and stones, and the discharge of the crater-lakes as torrents of water or of mud. In them there is nothing unusual, but as soon as the throat of the crater is thoroughly cleared, and the climax of the eruption is reached, a mass of incandescent lava rises and wells over the lip of the crater in the form of an avalanche of red-hot dust, which rushes down the slopes of the hill, carrying with it a terrific blast, which mows down everything in its path. The mixture of dust and gas behaves in many ways like a fluid. The exact chemical composition of these gases remains unsettled. They apparently consist principally of steam and sulphurous acid."[1]

In the investigation of the subject, the student will naturally devote attention specially to those aspects of volcanic action which have more particular geological interest from the permanent changes with which they are connected, or from the way in which they enable us to detect and realise conditions of volcanic energy in former periods.

**Fissures.**—The convulsions which culminate in the formation of a volcanic cone sometimes split open the terrestrial crust by a more or less nearly rectilinear fissure, or by a system of fissures. In the subsequent progress of the mountain, the ground at and around the focus of action is liable to be again and again rent open by other fissures. These tend to diverge from the focus; but around the vent where the rocks have been most exposed to concussion, the fissures sometimes intersect each other in all directions. In the great eruption of Etna, in the year 1669, a series of six parallel fissures opened on the side of the mountain. One of these, with a width of two yards, ran for a distance of 12 miles, in a somewhat winding course, to within a mile of the top of the cone.[2] Similar fissures have often been observed on Vesuvius and other volcanoes.[3] A fissure sometimes re-opens for a subsequent eruption.

Two obvious causes may be assigned for the pushing upward of a crater-floor and the fissuring of a volcanic cone:—(1) the enormous pressure of the dissolved vapours or gases acting upon the walls and roof of the funnel and convulsing the cone by successive explosions; and (2) the hydrostatic pressure of the lava-column in the funnel, which may be taken to be about 120 lbs. per square inch, or nearly 8 tons on the square foot, for each 100 feet of depth. Both of these causes may act

[1] Anderson and Flett, *Proc. Roy. Soc.* lxx. (1902), p. 444. The incandescent dust and sand, mingled with vapours, rolled like a liquid down into the valleys and accumulated there.

[2] For fissures on Etna, see Silvestri, *Boll. R. Geol. Com. Ital.* 1874.

[3] For a description of those of Iceland (which run chiefly N.E. to S.W., and N. to S.), see T. Kjerulf, *Nyt. Mag.* xxi. p. 147. The great Laki fissure of 1783 and other Icelandic chasms are further noticed in the account of fissure-eruptions on p. 342.

simultaneously, and their united effect has been to uplift enormous superincumbent masses of solid rock and to produce a widespread series of long and continuous fissures reaching from unknown depths to various distances from the surface and even opening up sometimes on the surface. These results of the expansive energy of volcanic action are of special interest to the geologist, for he encounters evidence of similar operations in former times preserved in the crust of the earth. (See Book IV. Part VII. Sect. i.)

Into rents thus formed, the water-substance or vapour rises with great expansive force, accompanied by the lava, which solidifies there like iron in a mould. Where fissures are vertical or highly inclined, the

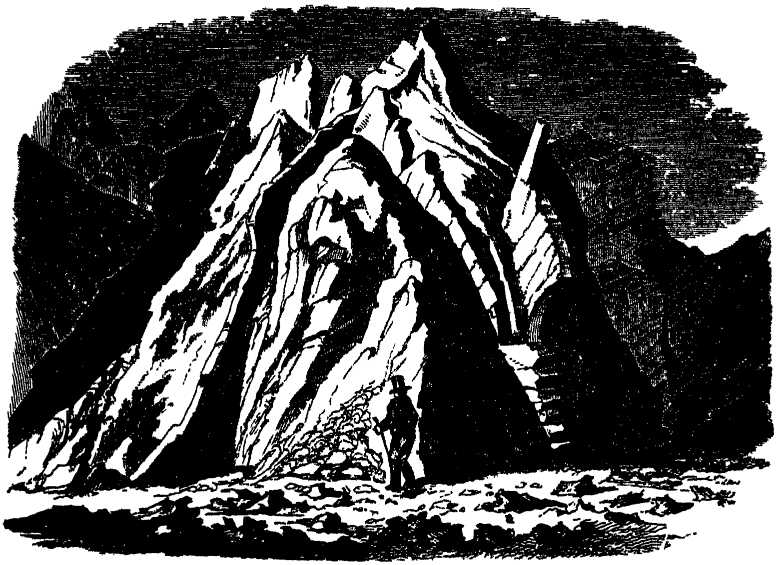

Fig. 41.—View of Lava-dykes, Valle del Bove, Etna (Abich).

igneous rock, on solidification there, takes the form of *dykes* or *veins;* where the intruded material has forced its way more or less in a horizontal direction between strata of tuff, beds of non-volcanic sediment or flows of lava, it takes the form of *sheets* (*sills*) or *beds.* The cliffs of many an old crater show how marvellously they have been injected by such veins, dykes or sheets of lava. The dykes of Somma, and the Valle del Bove on Etna (Fig. 41), which have long been known, project now from the softer tuffs like walls of masonry.[1] The crater cliffs of Santorin also present an abundant series of dykes. Occasionally examples may be seen of dykes which have risen to the surface in their fissures and then have flowed out at the surface. A section showing this structure was exposed by a landslip on the side of the cone of Vesuvius in May 1885. Instances have likewise been observed where, after being injected into a

[1] S. von Waltershausen, 'Der Aetna,' ii. p. 341.

fissure and adhering to its cool walls, the still fluid lava in the centre has escaped below, leaving a hollow dyke, with only a thin crust of its substance on either side.

The permanent separation of the walls of fissures by the consolidation of the lava that rises in them as dykes must widen the dimensions of a cone, for the fissures are not due to shrinkage, although doubtless the loosely piled fragmentary materials, in the course of their consolidation, develop lines of joint. Sometimes the lava has evidently risen in a state of extreme fluidity, and has at once filled the rents prepared for it, cooling rapidly on the outside as a true volcanic glass, but assuming a dis-

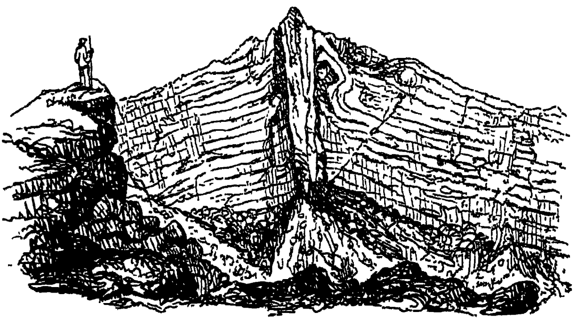

Fig. 42.—Dyke contorting beds of tuff. Crater of Vesuvius (Abich).

tinctly crystalline structure inside (*ante*, p. 236). Dykes of this kind, with a vitreous crust on their sides, may be seen on the crater-wall of Somma, and not uncommonly among basalt dykes in Iceland and Scotland.

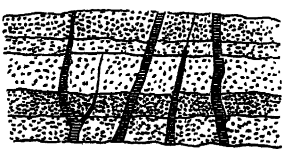

Fig. 43.—Section of Dykes of Lava traversing the bedded tuffs of a volcanic cone.

In other cases, the lava had probably already acquired a more viscous or even lithoid character ere it rose in the fissure, and in this condition was able to push aside and even contort the strata of tuff through which it made its way (Fig. 42). There can be little doubt that in the architecture of a volcano, dykes must act the part of huge beams and girders (Fig. 43), binding the loose tuffs and intercalated lavas together, and strengthening the cone against the effects of subsequent convulsions.

From this point of view, an explanation suggests itself of the observed alternations in the character of a volcano's eruptions. These alternations may depend in great measure upon the relation between the height of the cone, on the one hand, and the strength of its sides on the other. When the sides have been well braced together by interlacing dykes, and further thickened by the spread of volcanic materials all over their slopes, they may resist the effects of explosion and of the pressure of the ascending lava-column. In this case, the volcano may find relief only from its summit; and if the lava flows forth, it will do so from the top of the cone. As the cone increases in elevation, however, the pressure from within upon its sides augments. Eventually egress is once more estab-

lished on the flanks by means of fissures, and a new series of lava-streams is poured out over the lower slopes (*postea*, p. 331).

In the deeper portions of a volcanic vent the convulsive efforts of the lava-column to force its way upward must often produce lateral as well as vertical rifts, and into these the molten material will rush, exerting as it goes an enormous upward pressure on the mass of rock overlying it. At a modern volcano these subterranean manifestations cannot be seen, but among the volcanoes of Tertiary and older time they have been revealed by the progress of denudation. Some of these older examples teach us the prodigious upheaving power of the sheets of molten rock intruded between volcanic or other strata. An account of this structure (sills, laccolites), with reference to some examples of it, will be found in Book IV. Part VII.

Though lava very commonly issues from the lateral fissures on a volcanic cone, it may sometimes approach the surface in them without actually flowing out. The great fissure on Etna in 1669, for example, was visible even from a distance, by the long line of vivid light which rose from the incandescent lava within. Again, it frequently happens that minor volcanic cones are thrown up on the line of a fissure, either from the congelation of the lava round the point of emission, or from the accumulation of ejected scoriæ round the fissure-vent. One of the most remarkable examples of this kind is that of the Laki fissure in Iceland, to which more special reference is made in the account of fissure-eruptions (§ 3, ii.).

**Explosions.**—Apart from the appearance of visible fissures, volcanic energy may be, as it were, concentrated on a given point, which will usually be the weakest in the structure of that part of the terrestrial crust, and from which the solid rock, shattered into pieces, is hurled into the air by the enormous expansive energy of the volcanic vapours (*postea*, § 5, p. 353). This operation has often been observed in volcanoes already formed, and has even been witnessed on ground previously unoccupied by a volcanic vent. The history of the cone of Vesuvius brings before us a succession of such explosions, beginning with the catastrophe of A.D. 79. So stupendous were the effects of that, or possibly in part of an earlier explosion, that the southern half of the ancient crater was blown away, and even now, in spite of all the lava and ashes that have been poured out during the last eighteen centuries, the site of that crater remains unfilled up and still half-encircled by its gigantic wall (Fig. 44). At every successive important eruption, a similar but minor operation takes place within the present cone. The hardened cake of lava forming the floor is burst open, and with it there usually disappears much of the upper part of the cone, and sometimes, as in 1872, a large segment of the crater-wall. The great explosion at the beginning of our era was followed by about 1500 years of comparatively feeble activity, when the volcano relapsed into the Solfataric phase or became even more quiescent. In 1631 came another great explosion, which brought the long interval of quietude to an end and ushered in a period of more or less continued activity, the Solfataric and Strombolian phases alternating, but varied

now and then by a more vigorous (Plinian) display of explosive and eruptive energy.

The Valle del Bove on the eastern flank of Etna is a chasm probably due mainly to some gigantic prehistoric explosion.[1] The islands of Santorin (Figs. 64 and 65) bring before us evidence of a prehistoric catastrophe of a similar nature, by which a large volcanic cone was blown up. The existing outer islands are a chain of fragments of the periphery of the cone, the centre of which is now occupied by the sea. In the year 1538 a new volcano, Monte Nuovo, was formed in 24 hours on the margin of the Bay of Naples.[2] An opening was drilled by successive explosions, and such quantities of stones, scoriæ and ashes were thrown out from it as to form a hill that rose 489 English feet above the sea-level, and was more than a mile and a half in circumference. The larger

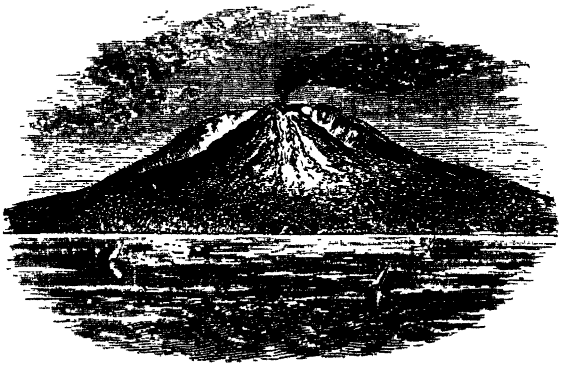

Fig. 44.—View of Vesuvius from the south, showing the remaining part of the old crater-wall of Somma behind.

part of the famous Lucrine Lake was filled up with the ejected materials. Most of the fragments now to be seen on the slopes of this cone and inside its beautifully perfect crater are of various volcanic rocks, many of them being black scoriæ; but pieces of Roman pottery, together with fragments of the older underlying tuff, and some marine shells, have been obtained—doubtless part of the soil and subsoil dislocated and ejected during the explosions.[3]

The most stupendous volcanic explosion on record was that of Krakatoa in the Sunda Strait on the 26th and 27th of August 1883.[4] After a series of convulsions, the greater portion of the island was blown out with a succession of terrific detonations which were heard more than 150 miles away, and the effect of which was to crack walls and windows in Batavia at a distance of 100 miles. A mass of matter, estimated at about 1⅛

[1] 'Der Aetna,' p. 400. Such vast explosion-craters are termed Calderas (p. 326).

[2] Sir W. Hamilton's 'Campi Phlegræi,' p. 70; Lyell's 'Principles,' i. p. 606. On the volcanoes of the PHLEGRAEAN FIELDS see Scrope's 'Volcanoes,' pp. 179, 247, 249, 315; R. T. Günther, *Geograph. Journ.* Oct.-Nov. 1897; G. de Lorenzo and C. Riva, "Il cratere di Vivara," *Atti Accad. Sci.*, Naples, x. (1900); G. de Lorenzo, "Considerazioni dell' origine superficiale dei Vulcani," *ibid.* xi. (1902); a good bibliography of the district will be found in Dr. Johnston-Lavis' 'Southern Italian Volcanoes.'

[3] There is a notice by C. de Stefani, "La villa di Cicerone ed un fenomeno precursore all' eruzione del Monte Nuovo," *Atti Accad. Lincei*, 3rd March 1901, p. 128.

[4] See 'The Eruption of Krakatoa,' by a Committee of the Royal Society, 1888. 'Krakatau,' R. D. M. Verbeck, Batavia, 1887.

cubic mile in bulk, was hurled into the air in the form of lapilli, ashes, and the finest volcanic dust. The effects of this volcanic outburst were marked both upon the atmosphere and the ocean. A series of barometrical disturbances passed round the globe in opposite directions from the volcano at the rate of about 700 miles an hour. The air-wave, travelling from east to west, is supposed to have passed three and a quarter times round the earth (or 82,200 miles) before it ceased to be perceptible.[1] The sea in the neighbourhood was thrown into waves, one of which was computed to have risen more than 100 feet above tide-level, destroying towns, villages, and 36,380 people. Oscillations of the water were perceptible even at Aden, 3800 geographical miles distant; at Port Elizabeth in South Africa, 4690 miles; and among the islands of the Pacific Ocean; and they are computed to have travelled in mid-ocean with a velocity averaging from 100 to 800 geographical miles in the hour.[2]

In the year 1886 the volcanic district of New Zealand was the scene of a sudden and violent explosion. Previous to that time the site had been known as one in which the usual closing manifestations of volcanic energy were displayed. Hot springs had built up a succession of geyserite terraces, and it seemed as if no further eruption need be expected. But suddenly, after a few preliminary shocks, a terrific explosion took place; vast quantities of sand and ashes with fragments of rock were hurled into the air; a chasm 2000 feet long, 500 feet broad and 300 feet deep was blown out of the southern slopes of Mount Tarawera, and was prolonged across the site of Lake Rotamahana, which disappeared. Seven powerful geysers sprang up on this chasm and hurled their columns of boiling water, steam, stones and mud to a height of 600 or 800 feet. After only about four hours the paroxysm was at an end, though vast volumes of steam continued to rise from the vents that had been opened, and the fairy-like terraces of geyserite were found to have been destroyed, their site being buried under mud and débris. No lava flowed out; steam appears to have been the great agent in the explosion.[3]

Another stupendous display of explosive energy took place on 15th July 1888, at the dormant volcano of Bandaisan in Northern Japan, at which no great eruptions had occurred for more than ten centuries. In a season of calm weather faint rumbling noises were first heard, followed by a tolerably severe earthquake, soon after which a succession of 15 or 20 terrific explosions shook the ground, and sent a vast column of steam and dust into the air. A large part of the mountain was broken up and the fragments were launched forward as a vast deluge of rocks and earth. It was computed that about 2800 million tons of material were thus displaced.[4]

It is not necessary, and apparently it seldom happens, that any liquid lava is erupted by such stupendous explosions that shatter the rocks through which the funnel passes. In none of the cases just cited is there any record of the outflow of molten rock. A similar fact is observable among the volcanic vents of former geological periods. Thus, among the cones of the extinct volcanic tract of the Eifel, some occur which consist entirely, or nearly so, of comminuted débris of the surrounding Devonian greywacke and slate through which the various volcanic vents have been opened (see pp. 326, 748). Evidently, in such cases, only elastic

[1] Scott and Strachey, *Proc. Roy. Soc.* xxxvi. (1883). *Royal Society's Report*, p. 57.

[2] Admiral Wharton, *Royal Society's Report*, p. 89. *Nature*, xxxix, (1889), p. 303.

[3] The eruption of Tarawera, New Zealand, in 1886, is described by Professor A. P. W. Thomas, 'Report on the Eruption of Tarawera,' published by the Government in 1888: also Professor Hutton's 'Report on the Tarawera Volcanic District,' Wellington, 1887; *Q. J. G. S.* xliii. (1887), p. 178.

[4] S. Sekiya and Y. Kikuchi, 'The Eruption of Bandaisan,' *Journ. Coll. Sci. Imp. Univ. Japan*, vol. iii. part ii. (1889).

vapours forced their way to the surface; and we see what probably often takes place in the early stages of a volcano's history, though the fragments of the underlying disrupted rocks are in most instances buried and lost under the far more abundant subsequent volcanic materials. Sections of small ancient volcanic "necks" or pipes sometimes afford an excellent opportunity of observing that these orifices were originally opened by the blowing out of the solid crust and not by the formation of fissures. Examples will be cited in later pages from Scottish volcanic areas of Old Red Sandstone, Carboniferous and Permian age. The orifices are there filled with fragmentary materials, wherein pieces of the surrounding and underlying rocks form a noticeable proportion[1] (p. 750).

A striking feature of volcanic explosions is their sudden and brief character. With little or no warning a communication is violently effected between the heated interior of the globe and the atmosphere outside, half a mountain is blown away or a new cone is thrown up, and after a few hours or days of activity the vent relapses again into a quiescence, which may once more last for centuries. The case of Monte Nuovo is full of suggestiveness in regard to the conditions under which volcanic vents may have been formed in past geological times. Here was an instance of the drilling of a volcanic funnel and the piling up of a cone around it to a height of nearly 500 feet in the course of a single day. It is probable that many of the "necks" just referred to as marking the sites of Palæozoic eruptions, are the records of equally sudden and transitory explosions. In such cases, we are perhaps presented with comparatively superficial effects of volcanic energy, due to the access of water to the magma within the crust and the consequent generation of superheated water-vapour, which eventually explodes, but without pouring forth the molten rock at the surface.

**Showers of Dust and Stones.**—A communication having been opened, either by fissuring or explosion, between the heated interior and the surface, fragmentary materials are commonly ejected from it, consisting at first mainly of the rocks through which the orifice has been opened, afterwards of volcanic substances. In a great eruption, vast numbers of red-hot stones are shot up into the air, and fall back partly into the crater and partly on the outer slopes of the cone. According to Sir W. Hamilton, cinders were thrown by Vesuvius, during the eruption of 1779, to a height of 10,000 feet. Instances are known where large stones, ejected obliquely, have described huge parabolic curves in the air, and fallen at a great distance.[2] Stones 8 lbs. in weight occur among the ashes which buried Pompeii. The volcano of Antuco in Chili is said to send stones flying to a distance of 36 (?) miles; Cotopaxi is reported to have hurled a 200-ton block 9 miles;[3] and the Japanese volcano, Asamá, is said to

[1] *Trans. Roy. Soc. Edin.* xxix. p. 458; *Quart. Journ. Geol. Soc.* (1892), President's Address, pp. 86, 118, 135, 143, 153.

[2] For a calculation of the parabola described by some of the stones projected from the crater of Vulcano during the eruption of 1888-90, see G. Grablovitz in 'Le Eruzioni dell' Isola di Vulcano,' p. 138.

[3] D. Forbes, *Geol. Mag.* vii. p. 320.

have ejected many blocks of stone, measuring from 40 to more than 100 feet in diameter.[1]

But in many great eruptions, besides a constant shower of stones and scoriæ, a vast column of exceedingly fine dust rises out of the crater, sometimes to a height of several miles, and then spreads outwards like a sheet of cloud. The remarkable fineness of this dust may be understood from the fact that during great volcanic explosions no boxes, watches, or close-fitting joints have been found to be able to exclude it.

Mr. Whymper collected some dust that fell 65 miles away from Cotopaxi, and which was so fine that from 4000 to 25,000 particles were required to weigh a grain.[2] So dense is the dust-cloud as to obscure the sun, and for days together the darkness of night may reign for miles around a volcano. In 1822, at Vesuvius, the ashes not only fell thickly on the villages round the base of the mountain, but travelled as far as Ascoli, which is 56 Italian miles distant from the volcano on one side, and as Casano, 105 miles on the other. The eruption of Cotopaxi, on 26th June 1877, began by an explosion that sent up a column of fine ashes to a prodigious height into the air, where it rapidly spread out and formed so dense a canopy as to throw the region below it into total darkness.[3] So quickly did it diffuse itself, that in an hour and a half, a previously bright morning became at Quito, 33 miles distant, a dim twilight, which in the afternoon passed into such darkness that the hand placed before the eye could not be seen. At Guayaquil, on the coast, 150 miles distant, the shower of ashes continued till the 1st of July. Dr. Wolf collected the ashes daily, and estimated that at that place there fell 315 kilogrammes on every square kilometre during the first thirty hours, and on the 30th of June 209 kilogrammes in twelve hours.[4] During a much less important eruption of the same mountain on the 3rd of July 1880, the amount of volcanic dust ejected, according to Mr. Whymper, could not have been less, and was probably vastly more, than two millions of tons, equivalent to a mass of lava containing more than 150,000 cubic feet.[5]

The explosion of Krakatoa in August 1883 was accompanied by the discharge of enormous quantities of volcanic dust, some of which was carried to vast distances. It was estimated that the clouds of fine dust were hurled from that volcano to a height of 17 miles, and the darkness which they caused extended for 150 miles from the focus of eruption. The diffusion and continued suspension of the finer particles of this dust in the upper air has been regarded as the probable cause of the remarkably brilliant sunsets of the following winter and spring over a large part of the earth's surface.[6] One of the most stupendous outpourings of volcanic ashes on record took place, after a quiescence of 26 years, from the volcano Coseguina, in Nicaragua, during the early part of the year 1835. On that occasion, utter darkness prevailed over a circle of 35 miles' radius, the ashes falling so thickly that, even 8 leagues from the mountain, they covered the ground to a depth of about 10 feet. It was estimated that the rain of dust and

[1] J. Milne, *Seism. Soc. Japan*, ix. p. 179, where an excellent account of the volcanoes of Japan is given. See also 'The Volcanoes of Japan,' by J. Milne and W. K. Burton (1892).

[2] *Royal Society Report on Krakatoa*, p. 183.

[3] During the comparatively insignificant eruption of this volcano in 1880 Mr. Whymper noticed that a column of inky blackness, formed doubtless of volcanic dust, went straight up into the air with such velocity that in less than a minute it had risen 20,000 feet above the rim of the crater, or 40,000 feet above the sea. 'Travels amongst the Great Andes,' p. 322.

[4] *Neues Jahrb.* 1878, p. 141. An account of this eruption is given by Mr. Whymper in his 'Travels amongst the Great Andes,' chap. vi.

[5] 'Travels amongst the Great Andes,' p. 328.

[6] *Royal Society Report*, pp. 151-463.

sand fell over an area at least 270 geographical miles in diameter. Some of the finer materials, thrown so high as to come within the influence of an upper air-current, were borne away eastward, and fell, four days afterwards, at Kingston in Jamaica—a distance of 700 miles. During the great eruption of Sumbawa, in 1815, the dust and stones fell over an area of nearly one million square miles, and were estimated by Zollinger to amount to fully fifty cubic miles of material, and by Junghuhn to be equal to one hundred and eighty-five mountains like Vesuvius. Towards the end of last century, during a time of great disturbance among the Japanese volcanoes, one of them, Sakurajima, threw out so much pumiceous material that it was possible to walk a distance of 23 miles upon the floating débris in the sea.

An inquiry into the origin of these showers of fragmentary materials brings vividly before us some of the essential features of volcanic action. We find that bombs, slags, and lapilli may be thrown up in comparatively tranquil states of a volcano, but that the showers of fine dust are discharged with greater violence, and only appear when the volcano becomes more energetic. Thus, at the constantly, but quietly, active volcano of Stromboli, where the column of lava in the pipe may be watched rising and falling with a slow rhythmical movement, the surface of the lava swells up into blisters several feet in diameter, which by and by burst with a sharp explosion that makes the walls of the crater vibrate. A cloud of steam rushes out, carrying with it hundreds of fragments of the glowing lava, sometimes to a height of 1200 feet. It is by the ascent of steam through its mass, that a column of lava is kept boiling at the bottom of the crater; and by the explosion of successive larger bubbles of steam, that the various bombs, slags, and fragments of lava are torn off and tossed into the air. It has often been noticed at Vesuvius that each great concussion is accompanied by a huge ball-like cloud of steam which rushes up from the crater. Doubtless it is the sudden escape of that steam which causes the explosion.

Differences in the amount of absorbed gases and vapours and also varying degrees of liquidity or viscosity in the lava probably affect the force of explosions. Minor explosions and accompanying scoriæ are abundant at Vesuvius, where the lavas are comparatively viscid; they are almost unknown at Kilauea, where the lava is remarkably liquid.

In tranquil conditions of a volcano, the steam, whether collecting into larger or smaller vesicles, works its way upward through the substance of the molten lava; and as the elasticity of this compressed vapour overcomes the pressure of the overlying lava, it escapes at the surface, and there the lava is thus kept in ebullition. But this comparatively quiet operation, which may be watched within the craters of many active volcanoes, does not produce clouds of fine dust. The collision or friction of millions of stones ascending and descending in the dark column above the crater doubtless gives rise to much dust and sand. But the explosive action of steam is probably the main cause of the production of these materials. The aqueous vapour or water-gas which is so largely dissolved in many lavas must exist within the lava-column, under an enormous pressure, at a temperature far above its critical point (p. 267), even at a white heat, and therefore probably in a state of dissociation. The sudden ascent of lava so constituted relieves the pressure rapidly without sensibly

affecting the temperature of the mass. Consequently, the white-hot gases or vapours at length explode, and reduce the molten mass to the finest powder, like water shot out of a gun.[1]

Evidently no part of the operations of a volcano has greater geological significance than the ejection of such enormous quantities of fragmentary matter. In the first place, the fall of these loose materials round the orifice of discharge is one main cause of the growth of the volcanic cone. The heavier fragments gather around the vent, and there too the thickest accumulation of dust and sand takes place. Hence, though successive explosions may blow out the upper part of the crater-walls and prevent the mountain from growing so rapidly in height, every eruption will increase the diameter of the cone, save in the occasional gigantic explosions, when half of a volcano may be blown away. In the second place, as every shower of dust and sand adds to the height of the ground on which it falls, thick volcanic accumulations may be formed far beyond the base of the mountain. The volcano of Sangay, in Ecuador, for instance, is said to have buried the country around to a depth of 4000 feet under its ashes.[2] In such loose deposits are entombed trees and other kinds of vegetation, together with the bodies of animals, as well as the works of man. Such deposits not only bear witness to the volcanic eruptions that produced them, but preserve a record of the land-surfaces over which they spread. In the third place, besides the distance to which the fragments may be hurled by volcanic explosions, or to which they may be diffused by the ordinary surface winds, we have to take into account the vast spaces across which the finer dust is sometimes borne by upper air-currents.

In the instance already cited, ashes from Coseguina fell 700 miles away, having been carried all that long distance by a high counter-current of air, moving apparently at the rate of about seven miles an hour in an opposite direction to that of the wind which blew at the surface. By the Sumbawa eruption, also referred to above, the sea west of Sumatra was covered with a layer of ashes two feet thick. On several occasions ashes from Icelandic volcanoes have fallen so thickly between the Orkney and Shetland Islands, that vessels passing there have had the unwonted deposit shovelled off their decks in the morning. In the year 1783, during the memorable eruption of Skaptar-Jökull, so vast an amount of fine dust was ejected that the atmosphere over Iceland continued loaded with it for months afterwards. It fell in such quantities over parts of Caithness—a distance of 600 miles—as to destroy the crops; that year is still spoken of by the inhabitants as the year of "the ashie." A similar deposit has from time to time fallen in Norway, and even as far as Holland.[3] Hence it is evident that volcanic accumulations may take place in regions many hundreds of miles distant from any active volcano. A single thin layer of volcanic detritus in a group of sedimentary strata would not thus of itself prove the existence of contemporaneous volcanic action in

[1] Messrs. Murray and Renard (*Proc. Roy. Soc. Edin.* xii. (1884), p. 480) concluded that the fragmentary condition and the fresh fractures of the dust-particles of the Krakatoa eruption were due to a tension phenomenon, which affects these vitreous matters in a manner analogous to what is observed in "Rupert's drops."

[2] D. Forbes, *Geol. Mag.* vii. p. 320.

[3] Nordenskiöld, *Geol. Mag.* (2), iii. p. 292. G. vom Rath, *Monatsb. K. Preuss. Akad. Wiss.* 1876, p. 282. *Neues Jahrb.* 1876, p. 52; and *postea*, p. 445.

its neighbourhood. Failing other proof of adjacent volcanic activity, it might have been wind-borne from a volcano in a distant region.

**Outflow of Lava.**—This appears to be immediately due to the expansion of the absorbed vapours and gases in the molten rock. Though, under the conditions which lead to great volcanic explosions, these vapours may reach the surface, without an actual outcome of lava, yet so intimately are vapours and lava commingled in the subterranean reservoirs, that in the normal phase of continued volcanic activity they commonly rise

Fig. 45.—View of houses surrounded and partly demolished by the Lava of Vesuvius, 1872.

together, and the explosions of the one lead to the outflow of the other. The first point at which the lava makes its appearance at the surface will largely depend upon the structure of the ground. Two causes have been assigned on a foregoing page (p. 286) for the fissuring of a volcanic cone. As the molten mass rises within the chimney of the volcano, continued explosions of vapour take place from its upper surface. The violence of these may be inferred from the vast clouds of steam, ashes, and stones hurled to so great a height into the air, and from the concussions of the ground, which may be felt at distances of more than 100 miles from the volcano. It need not be a matter of surprise, therefore, that the sides of a great vent, exposed to shocks of such intensity, should at last give way, and that large divergent fissures should be opened down the cone. Again, the hydrostatic pressure of the column of lava must, at a depth of 1000 feet below the top of the column, exert a pressure of between 70 and 80 tons on each square foot of the surrounding walls (p. 286). We may well believe that such a force, acting upon the walls of a funnel already shattered by a succession of terrific explosions, may prove too great for their resistance. When this happens, the lava

pours forth from the outside of the cone. On a much-fissured cone, lava may issue freely from many points, so that a volcano so affected has been graphically described as "sweating fire."

In a lofty volcano, lava occasionally rises to the lip of the crater and flows out there; but more frequently it escapes from some fissure or orifice in a weak part of the cone. In minor volcanoes, on the other hand, where the explosions are less violent, and where the thickness of the cone in proportion to the diameter of the funnel is often greater, the lava very commonly rises into the crater. Should the crater-walls be too weak to resist the pressure of the molten mass, they give way, and the lava rushes out from the breach. This is seen to have happened in

Fig. 46.—View of one of the Tuff-cones of Auvergne, broken down on one side by the escape of a stream of Lava. (After Scrope.)

several of the puys of Auvergne, so well figured and described by Scrope (Fig. 46). But if the crater be massive enough to withstand the pressure, the lava may at last flow out from the lowest part of the rim.

In a tall column of molten lava, there may be a variation in the density of its different parts, the heaviest naturally gravitating to the bottom. It has been observed by Ch. Vélain that at the Isle of Bourbon (Réunion), the lavas escaping from the base of the volcanic cone are denser and more basic than those which flow out from the lip of the crater.[1]

As soon as the molten rock reaches the surface, the superheated water-vapour or gas, dissolved within its mass, escapes copiously, and hangs as a dense white cloud over the moving current. The lava-streams of Vesuvius sometimes appear with as dense a steam-cloud at their lower ends as that which escapes at the same time from the main crater. Even after the molten mass has flowed several miles, steam continues to rise abundantly both from its end and from numerous points along its surface, and continues to do so for many weeks, months, or it may be for several years.

Should the point of escape of a lava-stream lie well down on the cone, far below the summit of the lava-column in the funnel, the molten rock,

on its first escape, driven by hydrostatic pressure, will sometimes spout up high into the air—a fountain of molten rock. This was observed in 1794 on Vesuvius, and in 1832 on Etna. In the eruption of 1852 at Mauna Loa, an unbroken fountain of lava, from 200 to 700 feet in height and 1000 feet broad, burst out at the base of the cone. Similar "geysers" of molten rock have subsequently been noticed in the same region. Thus in March and April 1868, four fiery fountains, throwing lava to heights varying from 500 to 1000 feet, continued to play for several weeks. According to Mr. Coan, such outbursts take place from the bottom of a column of lava 3000 feet high. The volcano of Mauna Loa strikingly illustrates another feature of volcanic dynamics in the position and out-

Fig. 47.—View of portion of a Lava-stream on Vesuvius (Abich).

flow of lava. It bears upon its flanks at a distance of 20 miles, but 10,000 feet lower, the huge crater Kilauea. As Dana has pointed out, these orifices form part of one mountain, yet the column of lava stands 10,000 feet higher in one conduit than in the other. On a far smaller scale the same independence occurs among the several pipes of some of the geysers in the Yellowstone region of North America.

From the wide extent of basalt-dykes, such as those of Tertiary age in Britain, which rise to the surface at a distance of 200 miles from the main remnants of the volcanic outbursts of their time, and are found over an area of perhaps 100,000 square miles, it is evident that molten lava may sometimes occupy a far greater space within the crust than might be inferred from the dimensions and outpourings even of the largest volcanic cone. There can be no doubt that vast reservoirs of melted rock, impregnated with superheated vapours, must formerly have existed, if they do

not exist still, beneath extensive tracts of country (p. 744). Yet even in these more stupendous manifestations of volcanism, the lava should be regarded rather as the sign than as the cause of volcanic action. It is doubtless the pressure of the imprisoned vapour, and its struggles to get free, which produce the subterranean earthquakes and the explosions from the vents. As soon as the vapour finds relief, the terrestrial commotion calms down again, until another accumulation of vapour demands a repetition of the same phenomena.

At its exit from the side of a volcano, lava glows with a white heat, and flows with a motion which has been compared to that of honey or of melted iron. It soon becomes red, and, like a coal fallen from a hot fireplace, rapidly grows dull as it moves along, until it assumes a black, cindery aspect. At the same time the surface congeals, and soon becomes solid enough to support a heavy block of stone. The aspect of the stream varies with the composition and fluidity of the lava, form of the ground, angle of slope, and rapidity of flow. Viscous lavas, like those of Vesuvius, break up along the surface into rough brown or black cinder-like slags and irregular ragged cakes, bristling with jagged points ("*aa*" [1]), which, in their onward motion, grind and grate against each other with a harsh metallic sound, sometimes rising into rugged mounds or becoming seamed with rents and gashes, at the bottom of which the red-hot glowing lava may be seen (Fig. 47). In lavas possessing somewhat greater fluidity, the surface presents froth-like, curving lines, as in the scum of a slowly flowing river, or is arranged in curious ropy folds, as the layers have successively flowed over each other and congealed ("*pahoehoe*" [1]). These and many other fantastic coiled shapes were exhibited by the Vesuvian lava of 1858, and are admirably displayed by the peculiarly liquid glassy lavas of Kilauea.[1] Acid and viscous lava-streams flow for comparatively short distances and do not spread out widely; they may even come to a stop on a steep slope like the obsidian on the north side of Vulcano. On the other hand, basic lavas, such as basalts, possessing much greater liquidity, have sometimes flowed for great distances and deluged vast tracts of country. A large area which has been flooded with lava is perhaps the most hideous and appalling scene of desolation anywhere to be found on the surface of the globe.

A lava-stream usually spreads out as it descends from its point of escape, and moves more slowly. Its sides look like huge embankments, or like some of the long mounds of "clinkers" in a great manufacturing district. The advancing end is often much steeper, creeping onward like a great wall or rampart, down the face of which the rough blocks of hardened lava are ever rattling (Fig. 45).

[1] For descriptions of Vesuvian lava-streams, see the various memoirs and works cited, *ante*, p. 267. For those of Etna, Sartorius von Waltershausen and A. von Lasaulx, 'Der Aetna,' ii. p. 390. The rugged scoriaceous lava-surfaces are known in Hawaii as *aa*, the smooth coiled and ropy surfaces are there called *pahoehoe*. Dana, 'Characteristics of Volcanoes,' p. 9. The same stream of lava may exhibit both these aspects in different parts of its course. *Ibid.* p. 209, and Dr. Johnston-Lavis' papers on Vesuvius, already cited, p. 267.

Rate of flow of Lava.—The rate of movement is regulated by the fluidity of the lava, by its volume, and by the form and inclination of the ground. Hence, as a rule, a lava-stream moves faster at first than afterwards, because it has not had time to stiffen, and its slope of descent is usually steeper than farther down the mountain. One of the most fluid and swiftly flowing lava-streams ever observed on Vesuvius was that erupted on 12th August 1805. It is said to have rushed down a space of 3 Italian ($3\frac{2}{3}$ English) miles in the first four minutes, but to have widened out and moved more slowly as it descended, yet finally to have reached Torre del Greco in three hours. A lava erupted by Mauna Loa in 1852 went as fast as an ordinary stage-coach, or fifteen miles in two hours; but some of the lavas from that mountain have in parts of their course moved with double that rapidity. Long after a current has been deeply crusted over with slags and rough slabs of lava, it may continue to creep slowly forward for weeks or even months. Thus the lava which began to flow from the side of Vesuvius on 3rd July 1895 was still moving four years afterwards, and had piled up a hill of black rock about 400 feet high.

It happens sometimes that, as the lava moves along, the still molten mass inside bursts through the outer hardened and deeply seamed crust, and rushes out with, at first, a motion much more rapid than that of the main stream. Any sudden change in the form or slope of the ground affects the flow of the lava. Thus, reaching the edge of a steep defile or cliff, it pours over in a cataract of glowing, molten rock, with clouds of steam, showers of fragments, and a noise utterly undescribable. Or, on the other hand, encountering a ridge or hill across its path, it accumulates until it either finds egress round the side or actually overrides and entombs the obstacle. The hardened crust or shell, within which the still fluid lava moves, serves to keep the mass from spreading. Here and there, inside this thickening crust, the lava subsides, when it can find egress lower down, leaving cavernous spaces and tunnels into which, when the whole is cold, one may enter, and which are sometimes festooned with stalactites of lava (p. 307).

Size of Lava-streams.—In some cases, lava escaping from craters or fissures comes to rest before reaching the base of the slopes, like the obsidian current, already referred to, which has congealed on the side of the cone of the island of Vulcano.[1] In other instances, the molten rock not only reaches the plains but flows for many miles away from the point of eruption. Sartorius von Waltershausen computed the lava emitted by Etna in 1865 at 92 millions of cubic metres, that of 1852 at 420 millions, that of 1669 at 980 millions, and that of a pre-historic lava-stream near Randazzo at more than 1000 millions.[2] The most stupendous outpouring of lava on record was that which took place near the Skapta Jökull in Iceland in the year 1783. Successive streams issued from the Laki fissure about 12 miles long, filling up river-gorges which were some-

[1] Recent eruptions in this island have consisted entirely of ashes and stones. A. Baltzer, *Z. D. G. G.* xxvi. (1875), p. 36, and the other papers already cited, p. 276.

[2] 'Der Aetna,' ii. p. 393.

times 600 feet deep and 200 feet broad, and advancing into the alluvial plains in lakes of molten rock 12 to 15 miles wide. Two currents of lava which, filling up the valley of the Skapta, escaped in nearly opposite directions, extended for about 28 and 50 miles respectively.[1]

Varying liquidity of Lava.—All lava, at the time of its expulsion, is in a molten condition. It usually consists of a glassy magma in which, by reason of the high temperature, most or even all of the mineral constituents are at first dissolved. As already remarked, however, considerable differences have been observed in the degree of liquidity, and consequently in the form and extent, of the outflows. Humboldt and Scrope long ago called attention to the thick, short, lumpy forms presented by masses of solidified trachytic rocks, which are lighter, more siliceous and more viscous, and to the thin, widely extended sheets assumed by basalts, which are heavy, contain much iron and basic silicates and have a greater liquidity.[2] The cause of this difference has been variously explained. It may depend partly upon chemical composition, the siliceous being naturally less fusible than the basic rocks. But as great differences of fluidity are observable even among lavas having nearly the same composition, there would seem to be some further cause for the diversity. Scrope, as far back as 1825, stated his belief that the liquidity of lava was to be traced to the presence of water-vapour in the magma.[3] Reyer, following this line of reasoning, has likewise maintained that we must look to original differences in the extent to which the subterranean igneous magma that supplied the lava has been saturated with vapours and gases. Molten rock highly impregnated gives rise, he holds, to fragmentary discharges, while when feebly impregnated it flows out tranquilly.[4] On the other hand, Captain C. E. Dutton, who has studied the volcanic phenomena of Western America and Hawaii, suggests that the different degrees of liquidity may depend not only on chemical differences, but on variations of temperature. He supposes that the basaltic lavas which have spread so far in thin sheets, and which must have had a comparatively great liquidity, flowed at temperatures far above that of their melting-point, and were, to use his phrase, "superfused."[5]

The varying degrees of liquidity are manifested in a characteristic way on the surface of lava. Thus, in the great lava-pools of Hawaii, the rock exhibits a remarkable liquidity, throwing up fountains of molten rock to a height of 300 feet or more. During its ebullition in the crater-pools, jets and driblets, a quarter of an inch in diameter, are tossed up, and, falling back on one another, make "a column of hardened tears of lava," one of which (Fig. 48) was found to have attained a height of 40 feet, while in other places the jets thrown up and blown aside by the wind give rise to long threads of glass which lie thickly together like mown grass, and are known by the natives under the name of "Pele's

[1] This eruption is further noticed at p. 342.

[2] Scrope, 'Considerations of Volcanoes' (1825), p. 93.

[3] *Ibid.* p. 25.

[4] 'Beitrag zur Physik der Eruptionen,' p. 77.

[5] 'High Plateaux of Utah,' *Geog. and Geol. Sur. Territories*, Washington (1880), chap. v.

hair," after one of their divinities.[1] Yet although the ebullition is caused by the uprise and escape of highly heated vapours, there is no cloud over the boiling lake itself, heavy white vapour only escaping at different points along the edge.

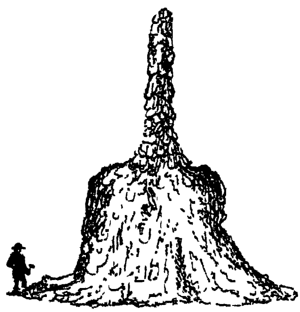

Fig. 48.—Column formed of congealed jets of liquid Lava, Crater of Kilauea (Dana).

On the other hand, the lavas of Vesuvius and of most modern volcanoes, which issue so saturated with vapour as to be nearly concealed from view in a cloud of steam, are accompanied by abundant explosions of fragmentary materials. Slags and clinkers, torn by explosions of steam from the molten rock, are strewn abundantly over the cone, while the surface of the lava is likewise rugged with similar clinkers, which may now and then be observed piled up round some more energetic steam-spiracle. Sometimes the vapour forces up the lava round such a spiracle or fumarole and gradually piles up a rugged column several feet or yards in height, as has been observed on Vesuvius[2] (Figs. 47, 49). So vast an amount of steam rushes out from one of these orifices, and with such boiling and explosion, that the cone of bombs, slags, and irregular lumps of lava forms a miniature or parasitic volcano, which will remain as a marked cone on its parent mountain long after the eruption which gave it birth has ceased. The lava of the eruption at Santorin in 1866-67 at first welled out tranquilly, but after a few days its outflow was accompanied by explosions and discharges of incandescent fragments, which increased until they had covered the lava dome with ejected scoriæ, and had opened a number of crateriform mouths on its summit.[3]

There can be no doubt, as above remarked, that the condition of liquidity of the lava has in some measure determined the character of the eruptions. In one case, there are quiet out-wellings of the more liquid lavas, as at Hawaii; in another, there are explosive discharges and cinder-cones accompanying the more viscid lavas, as at most modern volcanoes. The former has been the condition favourable to the most colossal outpourings of molten rock, as we see in the basalt-plateaux of Britain, Faroe, Iceland, Greenland, Idaho and Oregon, the Ghauts, Abyssinia, &c. This subject is again referred to at p. 342.

Crystallisation of Lava.—Pouring forth with a liquidity like that of molten iron, lava speedily assumes a more viscous condition and a slower motion. Obsidian and other vitreous rocks have consolidated as glass: yet that they did not flow with great liquidity is indicated by

[1] Dana, *Geol. U. S. Explor. Exped.*, "Geology," p. 179; 'Characteristics of Volcanoes,' p. 160. "Pele's hair" is sometimes carried by wind from the summit of Mauna Loa to Hilo, a distance of 35 miles. *Amer. Journ. Sci.* xxxvi. (1888), p. 83.

[2] Some good examples were observed on this mountain in the summer of 1891 by Dr. Johnston-Lavis, *Brit. Assoc.* 1891, Sect. C, where figures of some of them are given.

[3] Fouqué, 'Santorin,' p. xv.

such facts as the arrest of the obsidian stream half-way down the steep northern slope of Vulcano. Even in such perfect natural glass as obsidian, microscopic crystallites and crystals are usually present, and in prodigious numbers (pp. 148, 213). In most lavas, devitrification has proceeded so far before the final stiffening, that the original glassy magma has passed into a more or less completely lithoid or crystalline mass.

Fig. 49.—Lava-column (eight feet high), Vesuvius (Abich).

That lava may possess an appreciably crystalline structure while still in motion, has often been proved at Vesuvius, where well-defined crystals of the infusible leucite may be observed in a molten magma of the other minerals, portions of the white-hot rock in this condition being ladled out, impressed with a stamp and suddenly congealed. The fluxion-structure above described (p. 153) furnishes interesting evidence of this fact in many ancient as well as modern lavas.

There is reason to believe that in the molten magma, before its outflow as lava, considerable progress may be made within the volcano in the development of some crystalline minerals out of the surrounding glass, and that this crystalline portion may be to some extent separated from the vitreous residue. Hence, where this separation has taken place, subsequent eruptions may give rise to a more crystalline and probably

more basic lava from one point of emission and a more glassy and probably more acid lava from another vent. Or we may conceive that the two portions of the magma may be subsequently mingled again in various proportions before eruption.[1] If the process of differentiation should continue, as seems natural, during the lapse of a whole cycle of a volcano's history, the earlier lavas would be more basic than the later.

The crystalline structure of lava has been supposed to be in some measure determined by the presence of the volcanic vapours and gases with which the molten rock is impregnated, the rapid escape of these vapours preventing the formation of the crystalline structure, and leaving the lava in the condition of a more or less perfect glass. But the experiments of MM. Fouqué and Michel-Lévy (*postea*, p. 404) have shown that rocks, having in every essential particular the characters of volcanic lavas, may be artificially produced under ordinary atmospheric pressure by simple dry fusion. There appears to be no doubt that the presence of water lowers the fusion-point of silicates, though what precise influence the dissolved vapours exert upon the ultimate consolidation of molten lava has yet to be ascertained (see p. 413). Difference in the rate of cooling has doubtless been an important, if not the main, factor in determining the various conditions of texture of lava-streams. The crystalline structure may be expected to be most perfect where, as within thick masses of rock, the cooling has been prolonged, and where, consequently, the crystals have had ample time and opportunity for their formation. On the other hand, the glassy structure may be expected to be specially shown where the cooling has been most rapid, as in the vitreous crust on the walls of dykes already referred to (pp. 236, 288). As has been ascertained from the examination of ancient volcanoes which have been dissected by denudation, rocks crystallising in the deeper parts of a volcanic vent usually possess a more coarsely crystalline structure than those which crystallise at or near to the surface (p. 721).

Temperature of Lava.—It would be of the highest interest and importance to know accurately the temperature at which a lava-stream first issues. Measurements not altogether satisfactory have been taken at various distances below the point of emission, where the moving lava could be safely approached. Experiments made at Vesuvius by Scacchi and Sainte-Claire Deville in 1855, by thrusting thin wires of silver, iron and copper into the lava, indicated a temperature of scarcely 700° C. (1228° Fahr.). Observations of a similar kind, made in 1819, when a silver wire $\frac{1}{50}$th inch in diameter at once melted in the Vesuvian lava of that year, gave a greatly higher temperature, the melting-point of silver being about 1800° Fahr. But copper wire has also been melted, the point of fusion of this metal being about 2204° Fahr. Evidence of the high temperature of lava has likewise been adduced from the alteration it has effected upon refractory substances in its progress, as where, at Torre del

[1] Compare the observation of Ch. Vélain cited *ante*, p. 297, and Judd, *Geol. Mag.* 1888, p. 1. The subject of differentiation in molten magmas will be more conveniently discussed in Book IV. Part VII. Sect. i., where the evidence regarding it furnished by bosses, sills, and dykes is under consideration; but see also *postea*, pp. 404-407.

Greco, it overflowed the houses, and was afterwards found to have fused the fine edges of flints, to have decomposed brass into its component metals, the copper actually crystallising, and to have melted silver, and even sublimed it into small octahedral crystals (p. 309). The lava of Santorin has caught up pieces of limestone, and has formed out of them nodules containing crystallised anorthite, augite, sphene, black garnet, and particularly wollastonite.[1] The initial temperature of lava, as it first issues from the Vesuvian funnel, is probably considerably more than 2000° Fahr. Obviously the dissolved water (or water-substance, for, as already remarked, the temperature is far above the critical point of water, and its component gases may exist dissociated) must possess as high a temperature as that of the white-hot lava in which it is contained. The existence of the elements of water at a white heat, even in rocks which have reached the surface, is a fact of no little significance in the theoretical consideration of hypogene action.

Inclination and thickness of Lava-flows.—It was at one time supposed that lava could not consolidate in beds on such steep slopes as those of most volcanoes. Hence arose the "elevation-crater theory" (described at p. 320), in which the inclined position of lavas round a volcanic vent was explained by upheaval after their emission. Observations all over the world, however, have now demonstrated that lava, with all its characteristic features, can consolidate on slopes of even 35° and 40°.[2] The lava in the Hawaiian Islands has cooled rapidly on slopes of 25°; that from Vesuvius, in 1855, is here and there as steep as 30°; while the older lavas in Monte Somma are sometimes inclined at 45°. On the east side of Etna, a cascade of lava, which in 1689 poured into the vast hollow of the Cava Grande, has an inclination varying from 18° to 48°, with an average thickness of 16 feet. On Mauna Loa some lava-flows are said to have congealed on slopes of 49°, 60°, and even 90°,[3] though in these cases it could only be a layer of rock, stiffening and adhering to the surface of the precipice. On the other hand, lava-streams have travelled considerable distances over ground that to the eye looks quite level. Among the Hawaiian Islands a declivity of 1° or less has been quite sufficient for the flow of the extremely liquid and mobile lavas of that region. In the great lava-fields of the Snake River region of the Western Territories of the United States, the basalts, which must also have been extremely liquid, have flowed over slopes of much less than 1°.[4] The breadth and length of a lava-stream, as well as the form of its surface, depend mainly upon the liquidity of the molten material at the time of outflow. Even when it consolidates on a steep slope, a stream of lava forms a sheet with parallel upper and under surfaces, a general uniformity of thickness, and often greater evenness of surface, than where the angle of descent is low. The thickness varies indefinitely; many basalts which have been poured out in a remarkably liquid condition have solidified in beds not more than 10

[1] Fouqué, 'Santorin,' p. 206.

[2] Lyell on the consolidation of lava on steep slopes, *Phil. Trans.* 1858.

[3] J. D. Dana, *Amer. Jour. Sci.* xxxv. (1888), p. 32.

[4] J. D. Dana, 'Characteristics of Volcanoes,' p. 12.

or 12 feet thick. On the other hand, more pasty lavas, and lavas which have flowed into narrow valleys, may be piled up in solid masses to a thickness of several hundred feet (pp. 301, 308).

Structure of a Lava-stream.—Lava-streams are sometimes nearly homogeneous throughout. In general, however, they each show three component layers. At the bottom lies a rough, slaggy mass, produced by the rapid cooling of the lava, and the breaking up and continued onward motion of the scoriform layer. The central and main portion of the stream consists of solid lava, often, however, with a more or less carious and vesicular texture. The upper part, as we have seen, may be a mass of rough broken-up slabs, scoriæ, or clinkers. The proportions borne by these respective layers to each other vary continually. Some of the more fluid ropy lavas of Vesuvius have an inconstant and thin slaggy crust; others may be said to consist of little else than scoriæ from top to bottom. Throughout the whole mass of a lava-current, but more especially along its upper surface, the absorbed or dissolved water-vapour expands with diminution of pressure, and, pushing the molten rock aside, segregates into small bubbles or irregular cavities. Hence, when the lava solidifies, these steam-holes are seen to be sometimes so abundant that a detached portion of the rock containing them will float in water (pp. 134, 214). They are often elongated in the direction of the motion of the lava-stream (Fig. 50). Sometimes, indeed, where the cells are numerous, their elongation in one direction gives a fissile structure to the rock.

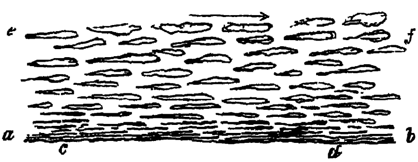

Fig. 50.—Elongation of Vesicles in direction of flow of Lava.

Some lavas, both acid and basic, assume columnar forms in cooling. The rhyolites of the Yellowstone National Park present this structure in a marked degree. The same characteristic is so common among basalts as to have made the term "basaltic" a popular synonym for "columnar." The columns diverge from the cooling surfaces; and as these are usually the top and bottom of a sheet, the columns are vertical where the sheet is horizontal and inclined where the sheet has flowed down a slope. In thick sheets and among basalts that apparently have possessed considerable mobility, the columns may be observed to be not infrequently curved and even undulating in form, and to be arranged in curiously irregular, sometimes fan-shaped groups, which start from different planes. To some of these forms of jointing more particular reference will be made in Book IV. Part II.

Another structure which has now been observed in many ancient and some modern lavas, especially those of more or less basic composition, consists in an aggregation of ellipsoids or irregularly pillow-shaped blocks, varying from a few inches to several feet or yards in diameter. These blocks are often markedly cellular towards the centre and finer-grained on the outer crust. They sometimes display lines of vesicles parallel with their margins. They belong to the time when the lava was still in movement and when it separated into globular portions, perhaps by flowing into water or muddy sediment.[1] The interspaces between the ellipsoids have been filled-in sometimes with fine volcanic tuff, sometimes with mud, limestone, ironstone or chert.

[1] Such globular lavas are well developed in Sicily. See G. Platania and H. J.

A singular feature of many lava-streams is to be seen in the tunnels and caverns already referred to (p. 300). These cavities have doubtless arisen during the flow of the mass when the upper and under portions had solidified and were creeping sluggishly onward, while the still molten interior was able to move faster or to escape and thus to leave empty spaces within. Such tunnels may frequently be seen among the Vesuvian lava-streams. A striking instance of them has been observed in a lava on the flanks of Mount Shasta, California. It is 60 to 80 feet high, 20 to 70 feet broad, with a roof from 10 to 75 feet thick, and has been penetrated for nearly a mile without coming to an end.[1] Interesting examples are described from the highly glassy lavas of Hawaii, where they are sometimes from 2 to 10 feet in height and 30 feet broad, but with large lateral expansions. The walls of these Hawaiian lava-chambers are smooth and even glassy, and from their roofs hang slender stalactites of lava 20 to 30 inches long, while on the floor below little mounds of lava-stalagmite have formed. The precise mode of origin of these curious appendages is not well understood.[2]

Vapours and sublimations of a Lava-stream.—Besides steam, many other vapours, absorbed in the original subterranean molten magma, escape from the fissures or fumaroles of a lava-stream (pp. 267-270). Among these exhalations chlorides abound, particularly chloride of sodium, which appears, not only in fissures, but even over the cooled crust of the lava, in small crystals, in tufts, or as a granular and even glassy incrustation. Chloride of iron is deposited as a yellow coating at Vesuvius, where also bright emerald-green films and scales of chloride of copper may be more rarely observed. Many chemical changes take place in the escape of these vapours. Thus specular-iron, either the result of the mutual decomposition of steam and iron-chloride, or of the oxidation of magnetite, forms abundant scales, plates, and small crystals in the fumaroles and vesicles of some lavas. Sal-ammoniac also appears in large quantity on many lavas, not merely in the fissures, but also on the upper surface, and perhaps as a result of the decomposition of aqueous vapour, whereby a combination is formed with atmospheric nitrogen. Sulphur, breislakite, szaboite, tenorite, alum, sulphates of iron, soda and potash, and other minerals are also found, as in the fumaroles of volcanic craters.

Slow cooling of Lava.—The hardened crust of a lava-stream is a bad conductor of heat. Consequently, the surface of the stream may have become cool enough to be walked upon, though the red-hot mass may be observed through the rents to lie only a few inches below. Many years, therefore, may elapse before the temperature of the whole mass has fallen to that of the surrounding soil. Eleven months after an eruption of Etna, Spallanzani could see that the lava was still red-hot at the bottom of the fissures, and a stick thrust into one of them instantly took fire. The Vesuvian lava of 1785 was found by Breislak, seven years afterwards, to be still hot and steaming internally, though lichens had already taken root on its surface. The ropy lava erupted by Vesuvius in 1858 was observed by the author in 1870 to be still so hot,

Johnston-Lavis, 'South Italian Volcanoes,' p. 41. They are of frequent occurrence among Palæozoic volcanic rocks. This structure is again noticed in Book IV. Part VII. Sect. ii. § 1.

[1] J. S. Diller, 'Mount Shasta, a Typical Volcano,' 1895.

[2] See Dana's 'Characteristics of Volcanoes,' pp. 209, 332-342.

even near its termination, that steam issued abundantly from its rents, many of which were too warm to allow the hand to be held in them; and three years later it was still steaming abundantly. Hoffmann records that from the lava which flowed from Etna in 1787, steam was still issuing in 1830. Yet more remarkable is the case of Jorullo, in Mexico, which sent out lava in 1759. Twenty-one years later a cigar could be lighted at its fissures; after 44 years it was still visibly steaming; and even in 1846, that is, after 87 years of cooling, two vapour-columns were still rising from it.[1]

This extremely slow rate of cooling has justly been regarded as a point of high geological significance, in regard to the secular cooling and probable internal temperature of our globe. Some geologists have argued, indeed, that if so comparatively small a portion of molten matter as a lava-stream can maintain a high temperature under a thin, cold crust for so many years, we may, from analogy, feel little hesitation in believing that the enormously vaster mass of the globe may, beneath a relatively thin crust, still continue in a molten condition within. Lord Kelvin, as already stated (p. 61), has suggested that, by measuring the temperature of intrusive masses of igneous rock in coal-workings and elsewhere, and comparing it with that of other non-volcanic rocks in the same regions, we might obtain data for calculating the time which has elapsed since these igneous sheets were erupted.

Effects of Lava-streams on superficial waters and topography.—In its descent, a stream of lava may reach a water-course, and, by throwing itself as an embankment across the stream, may pond back the water and form a lake. Such is the origin of the picturesque Lake Aidat in Auvergne. Or the molten current may usurp the channel of the stream, and completely bury the whole valley, as has happened again and again in the volcanic districts of Central France and among the vast lava-fields of Iceland. Few changes in physiography are so rapid and so enduring as this. The channel which has required, doubtless, many thousands of years for the water laboriously to excavate, is sealed up in a few hours under 100 feet or more of stone, and another vastly protracted interval must elapse before this newer pile is similarly eroded.[2]

By suddenly overflowing a brook or pool of water, molten lava sometimes has its outer crust shattered to fragments by a sharp explosion of the generated steam, while the fluid mass within rushes out on all sides.[3] A remarkable instance of this effect was witnessed on 16th October 1894, when an eruption took place on the island of Ambrym, one of the group of the New Hebrides in the south-west Pacific Ocean. The lava was seen to enter the sea with a roaring and hissing noise, sending up immense volumes of

[1] E. Schleiden, quoted by Naumann, 'Geognosie,' i. p. 160.

[2] The usurpation of river-beds by lava-streams and the subsequent progress of the running water in excavating new channels are admirably exemplified in Central France. See Scrope's volume on that region, where the phenomena are well described and illustrated with excellent drawings. For an example of the conversion of a lava-buried river-bed into a hill-top by long-continued denudation, see *Q. J. G. S.* (1871), p. 303.

[3] Explosions of this nature have been observed on Etna, where the lava has suddenly come in contact with water or snow, considerable loss of life being sometimes the result. Sartorius von Waltershausen and A. von Lasaulx, 'Der Aetna,' i. pp. 295, 300.

steam and discharging pieces of the rock in all directions, like the setting off of hundreds of rockets.[1]

The lava emitted by Mauna Loa, Hawaii, in the spring of 1868 flowed out to sea and added half a mile to the extent of the island at that point. At the end of the stream three cinder-cones formed from the contact of the lava with the water, and Captain Dutton calls special attention to the fact that not only in this instance, but in other examples among the Hawaiian lavas which have reached the sea, there is clear evidence of the formation of volcanic craters by the accidental contact of lava with water.[2] The lavas of Etna and Vesuvius have also protruded into the sea, but, owing probably to their more viscous and lithoid condition and lower temperature, they do not seem to have given rise to explosive action at their seaward ends. Thus a current from the latter mountain entered the Mediterranean at Torre del Greco in 1794, and pushed its way for 360 feet outwards, with a breadth of 1100 and a height of 15 feet. So quietly did it advance, that Breislak could sail round it in a boat and observe its progress. The ellipsoidal structure of some lavas, above alluded to, has been by some observers referred to the influence of water and mud upon the molten rock invading a lake or the sea.

By the outpouring of lava, two important kinds of geological change are produced:—(1) Stream-courses, lakes, ravines, valleys, in short, all the minor features of a landscape, may be completely overwhelmed under a thick sheet of lava. The drainage of the district being thus effectually altered, the numerous changes which flow from the operations of running water over the land are arrested and made to begin again in new channels. (2) Considerable alterations may likewise be caused by the effects of the heat and vapours of the lava upon the subjacent or contiguous ground. Instances have been observed in which the lava has actually melted down opposing rocks, or masses of slags on its own surface. Interesting observations, already referred to (p. 305), have been made at Torre del Greco under the lava-stream which overflowed part of that town in 1794. It was found that the window-panes of the houses had been devitrified into a white, translucent, stony substance; that pieces of limestone had acquired an open, sandy, granular texture, without loss of carbon-dioxide; and that iron, brass, lead, copper, and silver objects had been greatly altered, some of the metals being actually sublimed. We can understand, therefore, that, retaining its heat for so long a time, a mass of lava may induce many crystalline structures, re-arrangements, or decompositions in the rocks over which it comes to rest, and proceeds slowly to cool. This is a question of considerable importance in relation to the behaviour of ancient lavas which, after having been intruded among rocks beneath the surface, have subsequently been exposed by denudation. (Book IV. Part VII.)

But, on the other hand, the exceedingly trifling change produced, even by a massive sheet of lava, has often been remarked with astonishment. On the flank of Vesuvius, vines and trees may be seen still flourishing on little islets of the older land-surface, completely surrounded by a flood of lava. Dana has given an instructive account of the descent of a lava-stream from Kilauea in June 1840. Islet-like spaces of forest were left

[1] For further details see *postea*, p. 335, and the official report by Captain H. E. Purey Cust, R.N., Admiralty Paper, 1896, and *Geograph. Journ.* viii. (1896), pp. 588, 602.

[2] *Ann. Rep. U. S. G. S.* 1882-83, p. 181.

in the midst of the lava, many of the trees being still alive. Where the lava flowed round the trees, the stumps were usually consumed, and cylindrical holes or casts remained in the lava, either empty or filled with charcoal. In many cases the fallen crown of the tree lay near, and so little damaged that the epiphytic plants on it began to grow again. Yet so fluid was the lava that it hung in pendent stalactites from the branches, which nevertheless, though clasped round by the molten rock, had barely their bark scorched. Again, for nearly 100 years there has lain on the flank of Etna a large sheet of ice, which, originally in the form of a thick mass of snow, was overflowed by lava, and has thereby been protected from the evaporation and thaw which would certainly have dissipated it long ago, had it been exposed to the air. The heat of the lava has not sufficed to melt it. Extensive tracts of snow were likewise overspread by lava from the same mountain in 1879. In other cases, snow and ice have been melted in large quantities by overflowing lava. The great floods of water which rushed down the flank of Etna, after an eruption of the mountain in the spring of 1755, and similar deluges at Cotopaxi, are thus explained.

One further aspect of a lava-stream may be noticed here—the effect of time upon its surface. While all kinds of lava must, in the end, crumble down under the influence of atmospheric waste and, where other conditions permit, become coated with soil, and support some kind of vegetation, yet extraordinary differences may be observed in the facility with which different lava-streams yield to this change, even on the flank of the same mountain. Every one who ascends the slopes of Vesuvius remarks this fact. After a little practice, it is not difficult there to trace the limits of certain lavas even from a distance, in some cases by their verdure, in others by their barrenness. Five hundred years have not sufficed to clothe with green the still naked surface of the Catanian lava of 1381; while some of the lavas of the present century have long given footing to bushes of furze.[1] Some of the younger lavas of Auvergne, which certainly flowed in times anterior to those of history, are still singularly bare and rugged. Yet, on the whole, where lava is directly exposed to the atmosphere, without receiving protection from occasional showers of volcanic ash, or where liable to be washed bare by heavy torrents of rain, its surface decays in a few years sufficiently to afford soil for stray plants in the crevices. When these have taken root they help to increase the disintegration; at last, as the rock is overspread, the traces of its volcanic origin fade away from its surface. Some of the Vesuvian lavas of the present century already support vineyards.

**Elevation and Subsidence.**—Proofs of changes of level, whether upward or downward, are most easily detected when they take place close to or at the margin of the sea, the surface of which serves as a datum-plane from which to determine their amount. Hence volcanic islands in the ocean are specially favourable places for the detection of such movements (pp. 332-342). We must not suppose, however, that changes of level are less frequent at more inland centres of volcanic activity,

[1] On the weathering of the Etna lavas, see 'Der Aetna,' ii. p. 397.

though it is not so easy there, without careful levellings, to prove their occurrence and extent. Where marine strata have been carried up above sea-level, they supply clear evidence of elevation. Such proofs are frequent among volcanic vents, like Etna, Vesuvius, and other Mediterranean volcanoes, which began their history as submarine vents, and owe their present dimensions not only to the accumulation of ejected materials, but also, to some extent, to an elevation of the sea-bottom.

After a period of great volcanic activity, subsidence or "sagging" may take place at and around the focus of discharge. Such a lowering of the ground, obviously most easily detected at sea-level, leads to the submergence of the tracts affected by it. Thus during the eruption of Santorin in 1866-67, very decided but extremely local subsidence took place near the vent in the centre of the old crater.

Though the interior of modern volcanic cones can be at the best but very partially examined, the study of the sites of long-extinct cones, laid bare after denudation, shows that subsidence of the ground has commonly taken place at and round a vent. Theoretically two causes may be assigned for this structure. In the first place, the mere piling up of a huge mass of material round a given centre tends to press down the rock underneath, as some railway embankments may be observed to have done, where they have been made on soft ground. This pressure must often amount to several hundred tons on the square foot. In the second place, the expulsion of volcanic material to the surface may leave cavities underneath, into which the overlying crust will naturally gravitate. These two causes combined, as suggested by Mr. Mallet, afford a probable explanation of the saucer-shaped depressions in which many ancient and some modern vents appear to lie.[1]

Among the records of volcanic action in past geological time many proofs are to be found that it took place in areas where the predominant terrestrial movement was one of subsidence. Thus among the Palæozoic systems of Britain the Cambrian, Silurian, Devonian, Carboniferous, and Permian volcanoes successively appeared, and their lavas and tuffs were carried down and buried under thousands of feet of sedimentary deposits.[2]

**Torrents of Water and Mud.**—We have seen that large quantities of water accompany many volcanic eruptions. In some cases, where ancient crater-lakes or internal reservoirs, shaken by repeated detonations, have been finally disrupted, the mud which has thereby been liberated has issued from the mountain. Such "mud-lava" (*lava d'acqua*), on account of its liquidity and swiftness of motion, is more dreaded for destructiveness than even the true melted lavas. On the other hand, rain or melted snow or ice, rushing down the cone and taking up loose volcanic dust, is converted into a kind of mud that grows more and more pasty as it descends. The mere sudden rush of such large bodies of water down the steep declivity of a volcanic cone cannot fail to effect

[1] Mallet, *Q. J. G. S.* xxxiii. p. 740. See also the account of "Volcanic Necks," in Book IV. Part VII.

[2] See this history given in detail in 'Ancient Volcanoes of Great Britain.'

much geological change. Deep trenches are cut out of the loose volcanic slopes, and sometimes large areas of woodland are swept away, the débris being strewn over the plains below.

One of these mud-lavas invaded Herculaneum during the great eruption of 79, and by quickly enveloping the houses and their contents, has preserved for us so many precious and perishable monuments of antiquity. In the same district, during the eruption of 1622, a torrent of this kind poured down upon the villages of Ottajano and Massa, overthrowing walls, filling up streets and even burying houses with their inhabitants. During the great eruption of Cotopaxi, in June 1877, enormous torrents of water and mud, produced by the melting of the snow and ice of the cone, rushed down from the mountain. Huge portions of the glaciers of the mountain were detached by the heat of the rocks below them, and rushed down bodily, breaking up into blocks. The villages all round the mountain to a distance of sometimes more than ten geographical miles were left deeply buried under a deposit of mud mixed with blocks of lava, ashes, pieces of wood, lumps of ice, &c.[1] Many of the volcanoes of Central and South America discharge large quantities of mud directly from their craters. Thus, in the year 1691, Imbaburu, one of the Andes of Quito, emitted floods of mud so largely charged with dead fish that pestilential fevers arose from the subsequent effluvia. Seven years later (1698), during an explosion of another of the same range of lofty mountains, Carguairazo (14,706 feet), the summit of the cone is said to have fallen in, while torrents of mud containing immense numbers of the fish *Pymelodus Cyclopum*, poured forth and covered the ground over a space of four square leagues.[2] The carbonaceous mud (locally called *moya*) emitted by the Quito volcanoes sometimes escapes from lateral fissures, sometimes from the craters. Its organic contents, and notably its siluroid fish, which are the same as those found living in the streams above ground, prove that the water is derived from the surface, and accumulates in craters or underground cavities until discharged by volcanic action. Similar but even more stupendous and destructive outpourings are said to have taken place from the volcanoes of Java, where wide tracts of luxuriant vegetation have at different times been buried under masses of dark grey mud, sometimes 100 feet thick, with a rough hillocky surface from which the top of a submerged palm-tree would here and there protrude.[3]

Between the destructive effects of mere water-torrents and that of these mud-floods there is, of course, the notable difference that, whereas in the former case a portion of the surface is swept away, in the latter, while sometimes considerable demolition of the surface takes place at first, the main result is the burying of the ground under a new tumultuous deposit by which the topography is greatly changed, not only as regards

[1] Wolf, *Neues Jahrb.* 1878, p. 133. Stübel, 'Die Vulkanberge von Ecuador,' p. 153.

[2] Stübel declares that all that has been reported about mud-streams as products of volcanic action in Ecuador is based on erroneous and incredible statements. 'Die Vulkanberge von Ecuador,' p. 403.

[3] See *ante*, p. 271, where the observations of Professor Wichmann on this subject are cited.

its temporary aspect, but in its more permanent features, such as the position and form of its water-courses.

**Effects of the Closing of a Volcanic Chimney—Sills and Dykes.**—A study of the volcanic phenomena of former geological periods, where the structure of the interior of volcanoes and their funnels has been laid bare by denudation, shows that in many cases a vent becomes plugged up by the ascent and consolidation of solid material in it, while yet the eruptive energy of the volcano, though diminishing, has not ceased. A time is reached when the ascending magma, impelled by pressure from below, can no longer overcome the resistance of the column of solid lava or compacted agglomerate which has sealed up the orifice of discharge, or at least when it can more easily force a passage for itself between the sedimentary strata on which the whole volcanic pile may rest, or between the lava-sheets at the base of the pile, or into fissures in either or both of these groups. Hence arise intrusive sheets or sills and dykes or veins (see p. 287). That these later manifestations of volcanic energy have sometimes taken place on a great scale is shown by the number and size of the sills which are found at the base of the Palæozoic volcanic groups of Britain, where this feature of volcanic action has been especially investigated. Thus the great Cambrian and Lower Silurian volcanic outflows of Arenig and Cader Idris in North Wales are underlain with a profusion of basic sills. The same structure re-appears so markedly among the volcanic groups of the later Palæozoic formations, and also in those of Tertiary age, that it must be regarded as marking an ordinary phase of volcanic action. But it remains of course invisible until in the progress of denudation a volcanic cone is cut down to the roots.

The dissection wrought by denudation has further shown that in many instances the plutonic forces have not succeeded in establishing a connection with the surface and thus producing true volcanic manifestations, but have only been able to inject the magma into fissures of the crust or to thrust it in great sheets between the bedding-planes of stratified formations. These uncompleted efforts to form volcanoes have given rise to dykes, veins, bosses, sills and laccolites. (Book IV. Part VII.)

**Exhalations of Vapours and Gases.**—A volcano, as its activity wanes, may pass into the Solfataric stage, when only volatile emanations are discharged. The well-known Solfatara near Naples, since its last eruption in 1198, has constantly discharged steam and sulphurous vapours. The island of Vulcano has now passed also into this phase, though giving vent to occasional explosions. Numerous other examples occur among the old volcanic tracts of Italy, where they have been termed *soffioni*.[1] Steam, escaping in conspicuous jets, sulphuretted hydrogen, hydrochloric acid and carbonic acid are particularly noticeable at these orifices. The vapours in rising condense. The sulphuretted hydrogen partially oxidises into sulphuric acid, which powerfully corrodes the surrounding rocks. The lava or tuff through

[1] The various gases, vapours and sublimates of such fumaroles have been enumerated, *ante*, pp. 265-270.

which the hot vapours rise is bleached into a white or yellowish crumbling clay, in which, however, the less easily corroded crystals may still be recognised *in situ*. At the same time, sublimates of sulphur or of chlorides may be formed, or the sulphuric acid attacking the lime of the silicates gives rise to gypsum, which spreads in a network of threads and veins through the hot, steaming, and decomposed mass. In this way, at the island of Vulcano, obsidian is converted into a snow-white, dull, claystone-like substance, with crystals of sulphur and gypsum in its crevices. As a final residue silica is deposited from solution at many orifices, and coats the altered rock with a crust of chalcedony, hyalite, opal, or some form of siliceous sinter. As the result of solfataric action, masses of rock are decomposed below the surface, and new deposits of alum, sulphur, sulphides of iron and copper, and layers of silica, &c., are formed above them. Examples have been described from Iceland, Lipari, Hungary, Terceira, Teneriffe, St. Helena, and many other localities.[1] The *lagoons* of Tuscany are basins into which the waters from soffioni are discharged, and where a precipitation of their dissolved salts takes place. Among the substances thus deposited are gypsum, sulphur, silica, and various alkaline salts; but the most important is boracic acid, the extraction of which constitutes a thriving industry. In Chili many solfataras occur among extinct volcanoes.[2]

Another class of gaseous emanations betokens a condition of volcanic activity further advanced towards final extinction. In these, the gas is carbon-dioxide, either issuing directly from the rock or bubbling up with water which is often quite cold. The old volcanic districts of Europe furnish many examples. Thus on the shores of the Laacher See—an ancient crater-lake of the Eifel—the gas issues from numerous openings called *moffette*, round which dead insects, and occasionally mice and birds, may be found. In the same region occur hundreds of springs more or less charged with this gas. The famous Valley of Death in Java contains one of the most remarkable gas-springs in the world. It is a deep, bosky hollow, from one small space on the bottom of which carbon-dioxide issues so copiously as to form the lower stratum of the atmosphere. Tigers, deer, and wild-boar, enticed by the shelter of the spot, descend and are speedily suffocated. Many skeletons, including those of man himself, have been observed. "Death Gulch" is the significant name given to another example of the accumulation of carbonic acid in Western America. It is a natural bear-trap, where bodies of grizzly bears and other animals have been noticed.[3]

[1] Von Buch, 'Canar. Inseln,' p. 232. Hoffmann, *Pogg. Ann.* 1832, pp. 38, 40, 60. Bunsen, *Ann. Chem. Pharm.* lxii. (1847), p. 10. Darwin, 'Volcanic Islands,' p. 29. Nasini, Anderlini and Salvadori, *Nature*, lviii. (1898), p. 269. L. Colomba on the alterations produced by solfataric action, *Bull. Soc. Geol. Ital.* xx. (1901), p. 223; also xix. (1900), p. 521. The name *Propylite*, as already mentioned (*ante*, p. 230), has been proposed by Rosenbusch to be restricted to certain andesites and allied rocks altered by solfataric action.

[2] Domeyko, *Ann. Mines* ix. (7e sér.) Large numbers of solfataras occur also in Iceland.

[3] J. A. Jaggar, *Pop. Sci. Monthly*, Feb. 1899.

**Geysers.**—Eruptive fountains of hot water and steam, to which the general name of Geysers (*i.e.* gushers) is given, from the examples in Iceland, which were the first to be seen and described, mark a declining phase of volcanic activity. The Great and Little Geysers, the Strokkr and other minor springs of hot water in Iceland, have long been celebrated examples. Another series in New Zealand, remarkable for the beauty of its sinter-terraces, was destroyed by the volcanic eruption in 1886 (*ante*, p. 291). But probably the most striking and numerous assemblage is that which has been brought to light in the north-west part of the territory of Wyoming, and which has been included within the "Yellowstone National Park"—a region set apart by the Congress of the United States to be for ever exempt from settlement, and to be retained for the instruction of the people. In this singular region the ground in certain tracts is honeycombed with passages which communicate with the surface by hundreds of openings, whence boiling water and steam are emitted. In most cases, the water remains clear, tranquil, and of a deep green-blue tint, though many of the otherwise quiet pools are marked by patches of rapid ebullition. These pools lie on mounds or sheets of sinter, and are usually edged round with a raised rim of the same substance, often beautifully fretted and streaked with brilliant colours. The eruptive openings usually appear on small, low, conical elevations of sinter, from each of which one or more tubular projections rise. It is from these irregular tube-like excrescences that the eruptions take place.

The term geyser is restricted to active openings whence columns of hot water and steam are from time to time ejected; the non-eruptive pools are only hot springs. A true geyser should thus possess an underground pipe or passage, terminating at the surface in an opening built round with deposits of sinter. At more or less regular intervals, rumblings and sharp detonations in the pipe are followed by an agitation of the water in the basin, and then by the violent expulsion of a column of water and steam to a considerable height in the air. In the Upper Fire Hole basin of the Yellowstone Park, one of the geysers, named "Old Faithful" (Fig. 51), ever since the discovery of the region has sent out a column of mingled water and steam every sixty-three minutes or thereabouts. The column rushes up with a loud roar to a height of more than 100 feet, the whole eruption not occupying more than about five or six minutes. The other geysers of the same district are more capricious in their movements, and some of them more stupendous in the volume of their discharge. The eruptions of the Castle, Giant, and Beehive vents are marvellously impressive.[1]

In examining the Yellowstone Geyser region in 1879, the author was specially struck by the evident independence of the vents. This was

[1] See *Hayden's Reports* for 1870 and for 1878, in the latter of which will be found a voluminous monograph on the Hot Springs by A. C. Peale. Comstock's Report in Jones's 'Reconnaissance of N.W. Wyoming, &c.,' 1874. T. A. Jaggar, *Amer. Journ. Sci.* May 1898. *Nature*, lviii. (1898), p. 261. Weed, *School of Mines Quarterly*, New York, xi. (1890), No. 4, p. 289. Andrée, *Neues Jahrb.* 1893, ii. p. 1. The deposits of hot springs are further referred to on pp. 195, 473, 611.

shown by their very different levels, as well as by their capricious and unsympathetic eruptions. On the same hill-slope, dozens of quiet pools, as well as some true geysers, were noticed at different levels, from the edge of the Fire Hole River up to a height of at least 80 feet above it. Yet the lower pools, from which, of course, had there been underground connection between the different vents, the drainage should have principally discharged itself, were often found to be quiet steaming pools without outlet, while those at higher points were occasionally in active eruption. It seemed also to make no difference in the height or tranquillity of one of the quietly boiling caldrons, when an active projection of steam and water was going on from a neighbouring vent on the same gentle slope.

Fig. 51.—View of Old Faithful Geyser, and others in the distance, Fire Hole River, Yellowstone Park.

Bunsen and Descloiseaux spent some days experimenting at the Icelandic geysers, and ascertained that in the Great Geyser, while the surface temperature is about 212° Fahr., that of lower portions of the tube is much higher—a thermometer giving as high a reading as 266° Fahr. The water at a little depth must consequently be 54° above the normal boiling-point, but it is kept in the fluid state by the pressure of the overlying column. At the basin, however, the water cools quickly. After an explosion it accumulates there, and eventually begins to boil. The pressure on the column below being thus relieved, a portion of the superheated water flashes into steam, and as the change passes down the pipe, the whole column of water and steam rushes out with great violence. The water thereafter gradually collects again in the pipe, and after an interval of some hours the operation is renewed. The experiments made by Bunsen proved the source of the eruptive action to lie in the hot part of the pipe. He hung stones by strings to different depths in the funnel

of the geyser, and found that only those in the higher part were cast out by the rush of water, sometimes to a height of 100 feet, while, at the same time, the water at the bottom was hardly disturbed at all. These observations give much interest and importance to the phenomena of geysers in relation to volcanic action. They show that the eruptive force in geysers is steam; that the water column, even at a comparatively small depth, may have a temperature considerably above 212°; that this high temperature is local; and that the eruptions of steam and water take place periodically, and with such vigour as to eject large stones to a height of 100 feet.[1]

The hot water comes up with a considerable percentage of mineral matter in solution. According to the analysis of Sandberger, water from the Great Geyser of Iceland contains in 10,000 parts the following proportions of ingredients: silica, 5·097; sodium-carbonate, 1·939; ammonium-carbonate, 0·083; sodium-sulphate, 1·07; potassium-sulphate, 0·475; magnesium-sulphate, 0·042; sodium-chloride, 2·521; sodium-sulphide, 0·088; carbonic acid, 0·557 = 11·872.[2]

When the water has reached the surface, it deposits the silica as a sinter on the surfaces over which it flows or on which it rests.[3] The deposit, which is not due to mere cooling and evaporation, is curiously aided by the presence of living algæ (*postea*, p. 611). It naturally takes place fastest along the margins of the pools. Hence the curiously fretted rims by which these sheets of water are surrounded, and the tubular or cylindrical protuberances which rise from the growing domes. Where numerous hot springs have issued along a slope, a succession of basins gives a curiously picturesque terraced aspect to the ground, as at the Mammoth Springs of the Yellowstone Park and at the now destroyed terraces of Rotamahana in New Zealand.

In course of time, the network of underground passages undergoes alteration. Orifices that were once active cease to erupt, and even the water fails to overflow them. Sinter is no longer formed round them, and their surfaces, exposed to the weather, crack into fine shaly rubbish like comminuted oyster-shells. Or the cylinder of sinter grows upward until, by the continued deposit of sinter and the failing force of the geyser, the tube is finally filled up, and then a dry and crumbling white pillar is left to mark the site of the extinct geyser.

**Mud-Volcanoes.**[4]—These are of two kinds: 1st, where the chief

[1] *Comptes rendus*, xxiii. (1846), p. 934. *Pogg. Annal.* lxxii. (1847), p. 159; lxxxiii. (1851), p. 197. *Ann. Chimie*, xxxviii. (1853), pp. 215, 385. The explanation proposed for the phenomena observed at the Great Geyser is probably not applicable in those cases where the mere local accumulation of steam in suitable reservoirs may be sufficient.

[2] *Annal. Chem. und Pharm.* 1847, p. 49. A series of detailed analyses of the hot springs of the Yellowstone National Park will be found in No. 47 of the *Bull. U. S. G. S.* 1888.

[3] For an account of the geyserite of the Yellowstone district, see papers by W. H. Weed, *Amer. Journ. Sci.* xxxvii. (1889), and *9th Ann. Rep. U. S. Geol. Surv.* 1890.

[4] On MUD-VOLCANOES, see Bunsen, *Liebig's Annual*, lxiii. (1847), p. 1; Abich, *Mém. Acad. St. Petersburg*, 7e sér. t. vi. No. 5, ix. No. 4; Daubeny's *Volcanoes*, pp. 264, 539; Buist, *Trans. Bombay Geograph. Soc.* x. p. 154; Roberts, *Journ. Roy. Asiatic Soc.* 1850; De Verneuil, *Mém. Soc. Géol. France*, iii. (1838), p. 4; Stiffe, *Q. J. G. S.* xxx. p. 50; Von

source of movement is the escape of gaseous discharges; 2nd, where the active agent is steam.

(1) Although not volcanic in the proper sense of the term, certain remarkable orifices of eruption may be noticed here, to which the names of *mud-volcanoes*, *salses*, *salinellen*, *air-volcanoes*, and *maccalubas* have been applied (Sicily, the Apennines, Caucasus, Kertch, Taman, mouth of the Indus). These are conical hills formed by the accumulation of fine and usually saline mud, which, with various gases, is continuously or intermittently given out from the orifice or crater in the centre. They occur in groups, each hillock being sometimes less than a yard in height, but ranging up to elevations of 100 feet or more. Like true volcanoes, they have their periods of repose, when either no discharge takes place at all, or mud oozes out tranquilly from the crater, and their epochs of activity, when large volumes of gas, and sometimes columns of flame, rush out with considerable violence and explosion, and throw up mud and stones to a height of several hundred feet. The gases play much the same part, therefore, in these phenomena that steam does in those of true volcanoes. They consist of marsh-gas and other hydrocarbons, carbon-dioxide, sulphuretted hydrogen, and nitrogen, with petroleum vapours. The mud is usually cold. In the water occur various saline ingredients, among which common salt generally appears; hence the name, *Salses*. Naphtha is likewise frequently present. Large pieces of stone, differing from those in the neighbourhood, have been observed among the ejections, indicative doubtless of a somewhat deeper source than in ordinary cases. Heavy rains may wash down the minor mud-cones and spread out the material over the ground; but gas-bubbles again appear through the sheet of mud, and by degrees a new series of mounds is once more thrown up.

There can be little doubt that this type of mud-volcano is to be traced to chemical changes in progress underneath. Dr. Daubeny explained them in Sicily by the slow combustion of beds of sulphur. The frequent occurrence of naphtha and of inflammable gas rather points to the disengagement of hydrocarbons from the access of water to metallic carbides (pp. 86, 270), possibly sometimes to the destructive distillation of seams of coal.

In connection with these gaseous emanations, reference may be made here to those instances, now observed in many parts of the world, where volatile hydrocarbons are given off from the ground without any visible manifestation of their presence until they are lighted. Such discharges occur in many of the districts where mud-volcanoes appear, as in Northern Italy, on the Caspian, in Mesopotamia, in Southern Kurdistan, and in many parts of the United States. It has been observed that they sometimes rise in regions where beds of rock-salt lie underneath; and as that rock has been ascertained often to contain compressed gaseous hydrocarbons, the solution of the rock by subterranean water, and the consequent liberation of the gas, has been offered as an explanation of these fire-wells. But it is where abundant petroleum exists underneath that the volatile hydrocarbons are most plentiful. In the oil regions of Pennsylvania, for example, certain sandy strata occur at various geological horizons whence large quantities of petroleum and gas are obtained. In making the borings

Lasaulx, *Z. D. G. G.* xxxi. p. 457; Gümbel, *Sitzb. Akad. München.* 1879; F. R. Mallet, *Rec. Geol. Surv. India*, xi. p. 188; H. Sjögren, *Jahrb. Geol. Reichsanst.* xxxvii. (1887), p. 233.

for oil-wells, reservoirs of gas as well as subterranean courses or springs of water are met with. When the supply of oil is limited but that of gas is large, a contest for possession of the bore-hole sometimes takes place between the gas and water. When the machinery is removed and the boring is abandoned, the contest is allowed to proceed unimpeded and results in the intermittent discharge of columns of water and gas to heights of 130 feet or more. At night, when the gas has been lighted, the spectacle of one of these "fire-geysers" is inconceivably grand.[1]

In the oil region of Baku on the Caspian similar phenomena are displayed. The escape of inflammable gas from the ground has there been known for many centuries, a temple having been erected by fire-worshippers at one of the places where the discharge is copious. The chief tower of the enclosure is built over one of the spots whence the gas rises most freely, so that the flame blazed from its top. Though now disused, this shrine is still preserved, and I have seen the gas lighted at it. In the same neighbourhood limestone is burnt by stacking it over a gas-escape and setting a light to the pile. Even from the bed of the Caspian Sea at some little distance from the shore, the gas continues to rise through the water, the surface of which in calm weather appears to be in a state of effervescence. When a piece of lighted rope is thrown on the spot the gas at once bursts into flame and burns on the surface of the sea until blown out by the wind. At some of the numerous oil-wells which have been sunk around Baku, the gas accumulates and at intervals rushes with great violence, carrying with it a large dark column of oil and water for fifty feet or more above the level of the ground.

Certain pseudo-volcanic effects have been produced by the ignition of beds of coal, particularly through the decomposition of pyrites, whereby a great heat is generated. The "burning hills" of Turkestan have been referred to the subterranean combustion of beds of Jurassic coal.[2]

(2) The second class of mud-volcano presents itself in true volcanic regions, and is due to the escape of hot water and steam through beds of tuff or some other friable kind of rock. The mud is kept in ebullition by the rise of steam through it. As it becomes more pasty and the steam meets with greater resistance, large bubbles are formed which burst, and the more liquid mud from below oozes out from the vent. In this way, small cones are built up, many of which have perfect craters atop. In the Geyser tracts of the Yellowstone region, there are instructive examples of such active and extinct mud-vents. Some of the extinct cones there are not more than a foot high, and might be carefully removed as museum specimens.

## § 3. Structure of Volcanoes.

We have now to consider the manner in which the various solid materials ejected by volcanic action are built up at the surface. This inquiry will be restricted here to the phenomena of modern volcanoes,

[1] Ashburner, *Proc. Amer. Phil. Soc.* xvii. (1877), p. 157. *Stowell's Petroleum Reporter*, 15th Sept. 1879. *Second Geol. Survey of Pennsylvania*, containing Reports by J. Carll, 1877, 1880. J. S. Newberry, "The First Oil Well," *Harper's Magazine*, Oct. 1890. On the naphtha districts of the Caspian Sea, Abich, *Jahrb. Geol. Reichs.* xxix. (1879), p. 165. H. Sjögren, *op. cit.* xxxvii. (1887), p. 47. C. Marvin, 'Region of Eternal Fire,' London, 1884. See also for phenomena in Gallicia, *Jahrb. Geol. Reichs.* xv. pp. 199, 351; xvii. p. 291; xviii. p. 311; xxxi. (1881), p. 131. *Proc. Inst. Civ. Engineers*, xlii. (1875), p. 343.

[2] J. Muschketoff, *Neues Jahrb.* (1876), p. 516.

including the active and dormant, or recently extinct, phases. Obviously, however, in a modern volcano we can study only the upper and external portions, the deeper and fundamental parts being still concealed from view. But the interior structure has been, in many cases, laid open among the volcanic products of ancient vents. As these belong to the architecture of the terrestrial crust, they are described in Book IV. The student is therefore requested to take the descriptions there given, in connection with the foregoing and present sections, as related chapters of the study of volcanism.

Confining attention at present to modern volcanic action, we find that the solid materials emitted from the earth's interior are arranged in two distinct types of structure, according as the eruptions proceed from large central orifices or from fissures that reach up to the surface. In the former case, volcanic cones are produced; in the latter, volcanic plateaux or plains.

### i. *Volcanic Cones.*

The type of the volcanic cone, or ordinary volcano, is now the most abundant and best known. From some weaker point of a fissure, or from a vent opened directly by explosion, volcanic discharges of gas and vapours, with or without their liquid and solid accompaniments, make their way to the surface. Where the explosive energy has been great, but has not expelled volcanic products, either as lava or as ashes and stones, the vent of discharge may be left as a cavity on the ground, around which the débris shot out of the funnel forms a low rim or a more or less perfect cone. More usually molten or fragmentary volcanic materials are ejected so as to form a conical hill or mountain, the form and size of which may greatly vary according to the nature and duration of the eruptions. But the typical form which may be recognised through all these variations is that of the cone of accumulation. As this cone increases in height, by successive additions of ashes or lava to its surface, these volcanic sheets are laid down upon progressively steeper slopes. The inclination of beds of lava, which must have originally issued in a more or less liquid condition, offered formerly a difficulty to observers, and suggested the famous theory of Elevation-craters (*Erhebungskratere*) of L. von Buch,[1] Élie de Beaumont,[2] and other geologists. According to this theory, the conical shape of a volcanic cone arises mainly from an upheaval or swelling of the ground, round the vent from which the materials are finally expelled. A portion of the earth's crust (represented in Fig. 53 as composed of stratified deposits, *a b g h*) was believed to have been pushed up like a huge blister, by forces acting from below (at *c*) until the summit of the dome gave way and volcanic materials were emitted. At first these might only partially fill the cavity (as at *f*), but subsequent eruptions, if sufficiently copious, would cover over the truncated edges of the pre-volcanic rocks (as at *g h*), and would be liable to further upheaval by a renewal of the original upward swelling of the site.

[1] *Pogg. Ann.* ix. x. xxvii. p. 169.

[2] *Bull. S. G. F.* iv. p. 357. *Ann. des Mines*, ix. and x.

It was a matter of prime importance in the interpretation of volcanic action to have this question settled. To Poulett Scrope, Constant Prévost, and Lyell, belongs the merit of disproving the Elevation-crater

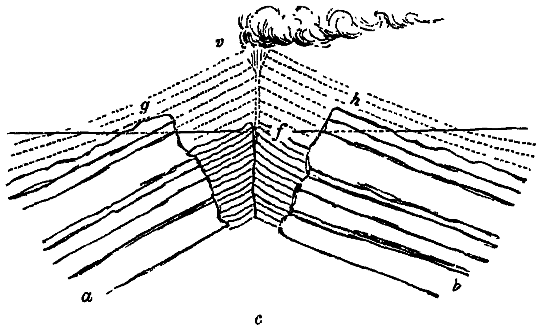


Fig. 52.—Section illustrative of the Elevation-crater Theory.

theory. Scrope showed conclusively that the steep slope of the lava-beds of a volcanic cone was original.[1] Constant Prévost pointed out that there was no more reason why lava should not consolidate on steep slopes than that tears or drops of wax should not do so.[2] Lyell, in successive

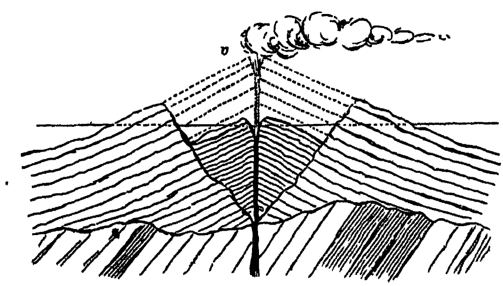


Fig. 53.—Diagram-section of a normal Volcano.

*x x*, Pre-volcanic platform, supposed here to consist of upraised stratified rocks, broken through by the funnel *f*, from which the cone of volcanic materials *c c* has been erupted. Inside the crater *v*, previously cleared by some great explosion, a minor cone may be formed during feebler phases of volcanic action, and this inner cone may increase in size until the original cone is built up again, as shown by the dotted lines.

editions of his works, and subsequently by an examination of the Canary Islands with Hartung, brought forward cogent arguments against the Elevation-crater theory.[3] A comparison of Fig. 52 with Fig. 53 will show at a glance the difference between this theory and the views of volcanic

[1] 'Considerations on Volcanoes,' 1825. 'The Geology of Central France,' 1826-27, 2nd edit. 1858. 'Volcanoes,' 2nd edit. 1872. "On the Formation of Cones and Craters and the nature of the Liquidity of Lavas," *Q. J. G. S.* xii. p. 326.

[2] *Comptes rendus*, i. (1835), p. 460; xli. (1855), p. 919. *Géol. Soc. France: Mémoires*, ii. p. 105, and *Bull.* xiv. p. 217. *Société Philom. Paris, Proc. Verb.* 1843, p. 13.

[3] *Phil. Trans.* 1858, p. 703. See the remarks of Fouqué, 'Santorin,' pp. 400-422.

structure now universally accepted. The steep declivities on which lava can actually consolidate have been referred to on p. 305.

The typical conical form of most volcanoes is that naturally assumed by a self-supporting mass of coherent material. It varies slightly according to the nature of the substance of the cone, the progress of atmospheric denudation, the position of the crater, the direction in which materials are ejected, the force and direction of the wind during an eruption, the growth of parasitic cones, and the collapse due to the dying out of volcanic energy.[1] The cone usually grows by additions made to its surface during successive eruptions, and though liable to great local variation of contour and topography, preserves its general form with singular persistence.

Among the Andes, however, another type than that of the normal cone has been developed. Huge masses of lava have there been built up into domes and pinnacled rocky isolated mountains, having a singular diversity of external form combined with a comparative simplicity of internal structure. Dr. Stübel, who has so sedulously studied the volcanoes of Ecuador, has announced his conviction, as the chief result of his study, that the majority of them have been formed, each as essentially the product of one single outbreak and not of a long series of widely separated eruptions. He thinks that while those volcanoes which have been gradually built up by repeated eruptions necessarily assume a conical form, those which have been produced in his opinion by a gigantic single effort possess great variety of shape. He does not mean to affirm that, in speaking of a single eruption, a volcano of a thousand or two thousand metres in height and corresponding width was produced in a few days, but only that the ejections by which the huge mass was piled up followed each other so closely that the volcano was practically completed before the mobility of its lava was arrested by cooling and consolidation. Thousands of years may have passed before the mass entirely cooled, yet none the less he would regard it as the product of a single eruption. A volcano formed in this way he terms *monogene;* while where it has been built up by the gradual accumulations of successive eruptions he calls it *polygene*.[2]

Many exaggerated pictures have been drawn of the steepness of slope in volcanic cones, but it is obvious that the angle cannot as a whole exceed the maximum inclination of repose of the detrital matter ejected from the central chimney.[3] A series of profiles of volcanic cones taken from photographs shows how nearly they approach to a common average type.[4] One of the most potent and constant agencies in modifying the outer forms of these cones is undoubtedly to be found in rain and torrents, which sweep down the loose detritus and excavate ravines on the declivities till a cone may be so deeply trenched as to resemble a half-opened umbrella.[5]

In the familiar Vesuvian type of volcano the top of the truncated cone bears the depression known as the crater, which doubtless owes its

[1] J. Milne, *Geol. Mag.* 1878, p. 339; 1879, p. 506; *Seismolog. Soc. Japan*, ix. p. 179. G. F. Becker, *Amer. Journ. Sci.* xxx. (1885), p. 283. H. J. Johnston-Lavis, *Geol. Mag.* 1888.

[2] 'Vulkanb. Ecuador,' p. 351.

[3] Cotopaxi is a notable example of such exaggerated representation. Mr. Whymper found that the general angles of the northern and southern slopes of the cone were rather less than 30° ('Travels amongst the Great Andes,' p. 123). Humboldt depicted the angle as one of 50°!

[4] See Milne, *Seism. Soc. Japan*, ix., and *Geol. Mag.* 1878, Plate ix.

[5] On the denudation of volcanic cones, see H. J. Johnston-Lavis, *Q. J. G. S.* xl. p. 103.

generally circular form to the equal expansion in all directions of the explosive vapours from below. In some of the mud-cones already noticed, the crater is not more than a few inches in diameter and depth. From this minimum, every gradation of size may be met with, up to huge precipitous depressions, several miles in diameter, and thousands of feet in depth. In the crater of an active volcano, emitting lava and scoriæ, like Vesuvius, the walls are steep, rugged cliffs of scorched and blasted rock—red, yellow, and black. Where the material erupted is only loose dust and lapilli, the sides of the crater are slopes, somewhat steeper than those of the outside of the cone (see Fig. 56).

The crater-bottom of an active volcano of the first class, when quiescent, forms a rough plain dotted over with hillocks or cones, from many of which steam and hot vapours are ever rising. At night, the glowing lava may be seen lying in these vents, or in fissures, at a depth of only a few feet from the surface. Occasional intermittent eruptions take place and miniature cones of slag and scoriæ are thrown up. In some instances, as in the vast crater of Gurung Tengger, in Java, the crater-bottom stretches out into a wide level waste of volcanic sand, driven by the wind into dunes like those of the African deserts.

Among the crater-bearing volcanoes there is usually at each mountain one chief crater, often also many minor ones, of varying or of nearly equal size. The volcano of the Isle of Bourbon (or Réunion) has three craters.[1] Not infrequently craters appear successively, owing to the blocking up of the pipe below. Thus in the accompanying plan of the volcanic cone of the island of Vulcanello (Fig. 54), one of the Lipari group, the volcanic funnel has shifted its position twice, so that three craters have successively appeared upon the cone, and partially overlap each other. A large volcano like Etna, besides its main crater, is sometimes crowded all over with small subsidiary cones communicating directly with the interior through the flanks of the cone, while sometimes smaller vents establish themselves for a time on the surface of flowing lava-streams. Such parasitic cones are referred to on p. 331.

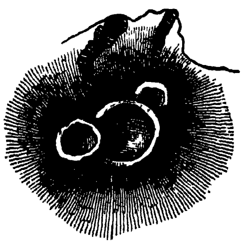

Fig. 54.—Plan of Vulcanello, showing three successive craters.

As already remarked, many important volcanoes, some of which still display activity, are without any crater. This feature is well displayed by the extinct trachytic puys of Auvergne, where the molten rock appears to have risen in a pasty condition, forming rounded domes, but not flowing over nor presenting any eruptive basin on the top. Mount Ararat has no crater, but so late as the year 1840 a fissure opened on its side, whence a considerable eruption took place. The most imposing group of

[1] For information regarding this volcanic island, see R. von Drasche, in *Verhandl. Geol. Reichsanst.* 1875, p. 266, and in *Tschermak's Min. Mittheil.* 1875 (3), p. 217 (4), p. 39; and his work, 'Die Insel Réunion (Bourbon),' 4to, Vienna, 1878. C. Vélain, 'Description géologique de la Presqu'île d'Aden, de l'Île de la Réunion, &c.,' Paris, 4to, 1878; and his work, 'Les Volcans,' 1884.

craterless volcanic cones is probably that presented by the great chain of the Andes. Among the volcanoes of Ecuador, Dr. Stübel distinguishes fourteen types, which he names after the mountains which best display these respective characters. Of these types a few possess summit craters, some show vast calderas with an opening on one side, but some of the most colossal, including Chimborazo, are vast domes with no crater, while others present at their summits a huge pyramid of rock.[1] The same author remarks that in the building up of volcanic mountains craters may play a part, but that they are not essential, and that in Ecuador gigantic accumulations of volcanic material have been formed without them. Their presence or absence probably depends mainly on the extent to which the underlying magma holds absorbed elastic vapours. If these vapours are present in large abundance and endowed with explosive energy they will probably blow out the outer part of the terrestrial crust and continue to keep the top of the volcanic chimney open by repeated clearances and the consequent formation of a growing crater. If, on the other hand, their quantity is comparatively small and their energy feeble, they may give rise to no explosion, and the lava may emerge with comparative tranquillity from openings on the side or even on the summit of the cone.

The following are the leading types of volcanic craters and cones :—

1. **Explosion-craters, Crater-lakes.**—It has occasionally happened that a volcanic eruption has consisted only of one transient explosion, whereby an opening has been drilled to the external atmosphere, but without the outburst of either volcanic ashes or lava. In such a case the material broken up from the orifice has fallen immediately around it, gathering into a low rim, or has been so triturated by the violence or continuance of the explosions as to be in great measure dispersed over the surrounding country. The form of the cavity is generally circular, and its size may range from a few yards to several miles. In the end, after perhaps a subsidence of the fragmentary materials in the vent, and even of the sides of the orifice, water supplied by rain and filtering from the neighbouring ground may partially, or wholly, fill up the cavity, so as to produce a lake either with or without a visible outlet. Under favourable circumstances, vegetation creeping over bare earth and stone may so conceal all evidence of the original volcanic action as to make the quiet sheet of water look as if it had always been an essential part of the landscape. Explosion-lakes (Crater-lakes) of this kind occur in districts of extinct volcanoes, as in the Eifel (*maare*),[2] Central Italy (Bolseno, Bracciano, Albano, Nemi,

[1] 'Vulkanb. Ecuador,' p. 399. Stübel classes his monogene volcanoes in several types, including Buttressed cones, some with a summit crater and others with a summit pyramid ; Caldera mountains (*ante*, p. 290); Dome mountains (Chimborazo). His polygene volcanoes he groups under one type, all showing traces of a central monogene cone (Cotopaxi, Tungurragua, Sangay), *loc. cit.* Von Seebach (*Z. D. G. G.* xviii. p. 644) distinguished two volcanic types :—1st, *Bedded Volcanoes* (Strato-Vulkane), composed of successive sheets of lava and tuffs, and embracing the great majority of volcanoes. 2nd, *Dome Volcanoes*, forming hills composed of homogeneous protrusions of lava, with little or no accompanying fragmentary discharges, without craters or chimneys, or at least with only minor examples of these volcanic features. He believed that the same volcano might at different periods in its history belong to one or other of these types—the determining cause being the nature of the erupted lava, which, in the case of the dome volcanoes, is less fusible and more viscid than in that of the bedded volcanoes. (See below, under "Lava-cones.")

[2] For works on the crater-lakes of the Eifel district see the references at the foot of p. 271.

&c.),[1] and Auvergne. The crateriform hollow called the Gour de Tazanat (67 metres deep), in Velay, has a diameter of half a mile and lies in the granite; while another cavity near Confolens, on the left bank of the Loire, has also been blown out of the granite and has given passage to no volcanic materials, but only to broken-up granite.[2] Other illustrations in Central France are to be found in the Lakes of Pavin (92 metres deep), Chauvet (63 metres), Issarlès (108 metres), and Ferrand.[3]

A remarkable example is supplied by the Lonar Lake in the Indian peninsula, half-way between Bombay and Nagpur.[4] It lies in the midst of the volcanic plateau of the Deccan traps, which extend around it for hundreds of miles in nearly flat beds that slightly dip away from the lake. An almost circular depression, rather more than a mile in diameter, and from 300 to 400 feet deep, contains at the bottom a shallow lake of bitter saline water, depositing crystals of trona (native carbonate of soda, the *nitrum* of the ancients). Except to the north and north-east, it is encircled with a raised rim of irregularly piled blocks of basalt, identical with that of the beds through which the cavity has been opened. The rim never exceeds 100 feet, and is often not more than 40 or 50 feet in height, and cannot contain a thousandth part of the material which once filled the crater. No other evidence of volcanic discharge from this vent is to be seen. Some of the contents of the cavity may have been ejected in fine particles, which have subsequently been removed by denudation; but it seems more probable that the existence of the cavity is mainly due to subsidence after the original explosion.[5]

Another striking illustration of the same structure is to be found in the Coon Butte on the arid limestone plains of north-eastern Arizona. The diameter of the bowl from rim to rim is about three-quarters of a mile; its depth below the crest of the rim is from 550 to 600 feet. The rim itself rises from 150 to 200 feet above the level of the plain around, and consists of limestone strata turned up so as to dip away steeply from the hollow on all sides, and covered by a mantle of loose blocks of limestone and sandstone, some of which are 100 feet in diameter. Some of the scattered fragments are found as far as three miles and a half from the place. So many fragments of meteoric iron have been found on the plain around that the idea was suggested that the depression had been caused by the impact of a meteorite. A careful survey of the ground by Mr. G. K. Gilbert led to the abandonment of this explanation. Within a radius of fifty miles there are hundreds of volcanic vents which have been active in geological time, and there seems no reason to doubt that the Coon Butte was suddenly blown out by a great explosion of pent-up volcanic vapour, as in the examples already quoted.[6]

North America has only one known crater-lake, but it is one of the most picturesque in the world. Deeply set in the summit of the Cascade Range of southern Oregon, its rim rises 1000 feet above the general level of the range, and from 520 to 1989 feet above the circular sheet of water, about six miles in diameter, which it encloses. The lake is 2000 feet deep, and the pit or basin in which it lies has its bottom 4000 feet below the surrounding crest. The rim is wholly composed of lava-sheets and beds of volcanic conglomerate, and the absence of the accumulation of débris, which would have been looked for had the basin been caused entirely by explosion, has led to the belief that though the original volcanic mountain, the rival of any of the remaining volcanic

[1] G. de Agostini (*Boll. Soc. Geograf. Ital.* 1898) has made a hydrographic exploration of the crater-lakes in the province of Rome.

[2] Tournaire, *B. S. G. F.* xxvi. (1869), p. 1166; Daubrée, *Comptes rend.* 1890, p. 859.

[3] A. Delebecque, 'Les Lacs Français,' Paris, 1898, p. 285. Scrope, 'Volcanoes of Central France,' pp. 81, 143, 144. Lecoq, 'Époques géologiques de l'Auvergne,' tome iv.

[4] See Malcolmson, *Trans. Geol. Soc.* 2nd ser. vol. v. p. 562; Medlicott and Blanford, 'Geology of India,' p. 379.

[5] This cavity may possibly mark one of the vents from which the basalt floods issued.

[6] G. K. Gilbert, Presidential Address, Geol. Soc. Washington, March 1896.

cones of the region, may have been blown away by a gigantic explosion, the deep Crater Lake, as it now exists, has probably been produced to a large extent by subsidence.[1]

Many volcanic cones have been eviscerated by one or more gigantic explosions, the bottoms of their craters have been blown out, and sometimes as much as half of the cone has been demolished, leaving a huge caldron-like hollow partially encircled by the remaining crater-wall, and bearing a far larger proportion to the size of the surrounding cone than an ordinary crater. Such a condition is known as the Caldera type of volcano, after the magnificent example of it in the island of Palma, one of the Canary group. This vast cavity is from three to four geographical miles in diameter, and is surrounded on all sides but the south-west by a range of precipices from 1500 to 2500 feet in vertical height, and rising along their higher summits to more than 7000 feet above the sea.[2] The Val del Bove in Etna is another well-known instance of a caldera, and even more familiar is the Atrio del Cavallo that lies between the modern cone of Vesuvius and the more ancient crater-wall of Somma. The type is well illustrated among the Andes. In Ecuador, Dr. Stübel enumerates eleven examples of it. Of these the most perfect is Rumiñahui, the crater-wall of which rises upwards of 800 metres above the bottom of the caldera to a height of 4757 metres above the sea. In two cases (Guagua-Pichincha and Pululagna) an eruptive cone has been formed within the caldera.[3] The great explosions of Krakatoa and Bandaisan (pp. 290, 291) have taught us how such vast caldron-like cavities may be produced within a few hours by sudden explosions. It is possible also, as above stated, that in some cases the depth of the hollows has been increased by a subsidence of the bottom, like that which appears to have occurred at Krakatoa.

2. **Cones of Non-volcanic Materials.**—These are due to the discharge of steam or other aeriform product through the solid crust without the emission of any true ashes or lava. The materials ejected from the cavity are wholly, or almost wholly, parts of the surrounding rocks through which the volcanic pipe has been drilled. Some of the cones surrounding the crater lakes (*maare*) of the Eifel consist chiefly of fragments of the underlying Devonian slates (p. 291), while some of those in Central France are built up mainly of granite. Such cones probably indicate brief explosions. Examples of similar conditions of eruption are furnished among the Carboniferous and later volcanic vents in Central Scotland, where the funnels of discharge are now found filled wholly or nearly so with fragments of the strata through which they have been drilled.

3. **Tuff-cones, Cinder-cones.**—Successive eruptions of fine dust and stones, often rendered pasty by mixture with the water so copiously condensed during an eruption, form a cone in which the materials are solidified by pressure into tuff. Cones made up only of loose cinders, often arise on the flanks or round the roots of a great volcano, as happens to a small extent on Vesuvius, and on a larger scale upon Etna. They likewise occur by themselves apart from any lava-producing volcano, though they often afford indications that columns of lava have risen in their funnels, and even now and then that this lava has reached the surface. The cone of Monte Nuovo, already referred to, is a typical example of this structure, and has peculiar interest and value, inasmuch as its eruption was actually witnessed and described (*ante*, p. 290).[4] It is a memorable example of the rapidity with which a considerable monticule of fragmentary volcanic materials may be thrown up and of the transient nature of the eruption.[5]

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[1] J. S. Diller, *Amer. Journ. Sci.* iii. (1897), p. 165. Special map, section and description published by the U. S. Geol. Survey; also *Nat. Geograph. Mag.*, Washington, Feb. 1897.

[2] Lyell, 'Elements of Geology,' edit. 1865, p. 621.

[3] 'Vulkanb. Ecuador,' pp. 165, 400.

[4] Some particulars in regard to this cone will be found in the paper by G. de Lorenzo cited on p. 290.

[5] On the transient character of the volcanic action in the case of tuff-cones, see Bishop, *Amer. Geol.* xxvii. (1901), p. 1.

Another historical example of the formation of a volcanic hill of a somewhat different type at a place where there had been earlier eruptions, but possibly before the human period, is to be seen on the peninsula of Methana in Greece. At that place, in the third century B.C., a hill of andesite blocks with a crater on the top was piled up to a height of 416·9 metres above the sea. As at Santorin, the lava appears to have risen to the surface as a cone or dome, which broke up into large angular blocks and sent a long stream of andesite into the sea. The flanks of the eminence have a slope of 37°, and are surmounted by a crater 100 to 150 metres in diameter, and from 60 to 80 metres in depth.[1]

The cones of the Eifel district have long been celebrated for their wonderful perfec-

Fig. 55.—View of the Tuff-cones of Auvergne, taken from the top of the cone and crater of Puy Pariou.

tion. Though small in size, they exhibit with singular clearness many of the leading features of volcanic structure. Those of Auvergne (Fig. 55) are likewise exceedingly instructive.[2] The high plateaux of Utah are dotted with hundreds of small volcanic cinder-cones, the singular positions of which, close to the edge of profound river-gorges and on the upthrow side of faults, have been noticed by Captain Dutton. Among the Carboniferous volcanic rocks of Central Scotland the stumps of ancient tuff-cones,

[1] A graphic account of this eruption is given by Strabo (i. 3, 18). It is more poetically and inaccurately described by Ovid (*Metamorphoses*, xv. 296-306). In modern times its site was first identified by Professor Fouqué (*Compt. rend.* lxii. pp. 904, 1121); *Revue des deux Mondes*, lviii. (1867), p. 470. The site was visited by Reiss and Stübel, 'Ausflug nach den vulkanischen Gebirgen von Aegina und Methana,' Heidelberg, 1867. See also K. von Seebach, *Z. D. G. G.* xxi. (1869), p. 275; Neumann and Partsch, 'Phys. Geogr. Griechenland,' Breslau, 1885, p. 306; H. S. Washington, *Journ. Geol.* ii. (1894), p. 789; iii. pp. 21, 138, where a detailed petrographical description of the volcanic rocks is given.

[2] For the Eifel cones see the works cited p. 271; for those of Auvergne, the references on p. 280.

frequently with a central core of basalt, or with dykes and veins of that rock, are of common occurrence.[1]

The materials of a tuff-cone are arranged in more or less regularly stratified beds. On the outer side, they dip down the slopes of the cone at the average angle of repose, which may range between 30° and 40°. From the summit of the crater-lip they likewise dip inward toward the crater-bottom at similar angles of inclination (Fig. 56).

**4. Mud-cones** resemble tuff-cones in form, but are usually smaller in size and less steep. They are produced by the hardening of successive outpourings of mud from the orifices already described (p. 318). In the region of the Lower Indus, where they are abundantly distributed over an area of 1000 square miles, some of them attain a height of 400 feet, with craters 30 yards across.[2]

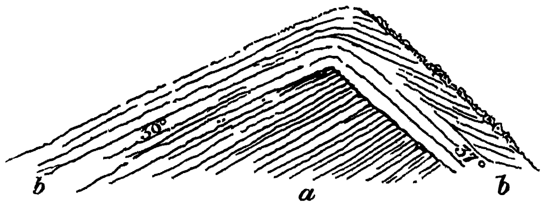


Fig. 56.—Section of the Crater-rim of the Island of Vulcano.
*a*, Older tuff; *b b*, younger ashes; the crater lies to the right.

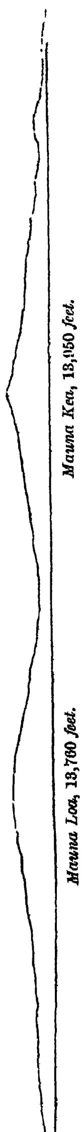


Fig. 57.—Profile of Lava-domes of Hawaii.

**5. Lava-cones.**—Volcanic cones composed entirely of lava are comparatively rare, but occur in some younger Tertiary and modern volcanoes. Fouqué describes the lava of 1866 at Santorin as having formed a dome-shaped elevation, flowing out quietly and rapidly without explosions. After several days, however, its emission was accompanied with copious discharges of fragmentary materials and the formation of several crateriform mouths on the top of the dome. Where lava possesses extreme liquidity, and gives rise to little or no fragmentary matter, it may build up a flat cone, as in the remarkable examples of the Hawaiian Islands.[3] On the summit of Mauna Loa (Fig. 57), a flat lava-cone 13,760 feet above the sea, lies a crater, which in its deepest part is about 8000 feet broad, with vertical walls of stratified lava rising on one side to a height of 784 feet above the black lava-plain of the crater-bottom. From the edges of this elevated caldron the mountain slopes outward at an angle of not more than 6°, until, at a level of about 10,000 feet lower, its surface is indented by the vast pit-crater, Kilauea (Fig. 58), about two miles long, and nearly a mile broad. So low are the surrounding slopes that these vast craters have been compared to open quarries on a hill or moor. The bottom of Kilauea is a lava-plain, dotted with lakes of extremely fluid lava in constant ebullition. The level of the lava has varied, for the walls surrounding the fiery flood consist of beds of similar lava, and are marked by ledges or platforms indicative of former successive heights of lava, as lake-terraces show former levels of water. In the accompanying section (Fig. 59) the walls rising above the lower pit (*p p'*) were found to be 342 feet

[1] *Trans. Roy. Soc. Edin.* xxix. p. 455. 'Ancient Volcanoes of Great Britain,' chaps. v. xxvi.-xxviii. xxxi. xli. Compare W. Branco, 'Schwabens 125 Vulkan-embryonen,' Stuttgart, 1894. See *postea*, Book IV. Part VII.

[2] Lyell, 'Principles,' ii. p. 77.

[3] Wilkes's *Report of U. S. Exploring Expedition*, 1838-42, and Dana's 'Characteristics of Volcanoes.' See the works cited on p. 317.

high; those bounding the higher terrace ($o\,n\,n'\,o'$) were 650 feet high, all being composed of innumerable beds of lava, as in cliffs of stratified rocks. Much of the bottom of the lower lava-plain has been crusted over by the solidification of the molten rock. But large areas, which shift their position from time to time, remain in perpetual rapid ebullition. The glowing flood, as it boils up with a fluidity more like that of water than what is commonly shown by molten rock, surges against the surrounding terrace-walls. Large segments of the cliffs, undermined by the fusion of their base, fall at intervals into the fiery waves and are soon melted. Observations by Captain Dutton in 1882 indicated at that time a diminution of the activity of this lava-crater. In Iceland, and in the Western Territories of North America, low domes of lava appear to mark the vents from which extensive basalt-floods have issued.

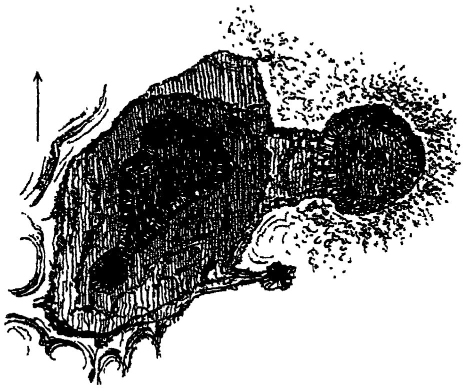

Fig. 58.—Plan of Lava-caldron, Kilauea, Hawaii (Dana, 1841).[1]

Where the lava assumes a more viscid character, as in trachyte and liparite, dome-shaped eminences may be protruded. As the pasty mass increases in size by the uprise of fresh material from below, the outer layer will be pushed outward, and successive shells will in like manner be enlarged as the eruption advances. On the cessation of discharges, we may conceive that a volcanic hill formed in this way will present an onion-like arrangement of its component sheets of rock. More or less perfect examples of this structure have been observed in Bohemia, Auvergne, and the Eifel.[2] The trachytic domes of Auvergne form a conspicuous feature among the cinder-cones of that region. Huge conical protuberances of granophyre, possibly of somewhat similar, but not superficial, origin, occur among the Tertiary volcanic rocks of the Inner Hebrides; and hills of liparite rise through the basalts of Iceland.[3]


Fig. 59.—Section of Lava-terraces in Kilauea (Dana).

Among the giant volcanoes of the Andes examples occur of lava pyramids and domes rising high above the surrounding country. Among those of Ecuador, Chimborazo (6310 metres, 20,702 feet) presents a remarkable uniformity of structure, as if it were the product of a single outburst or protrusion of lava. Not only does it possess no crater, but its mass of solidified lava vastly exceeds that of the fragmentary materials.[4] No eruption is known to have occurred from it since the discovery of America.

[1] For more recent maps showing the variations of this crater, see Dana's papers in *Amer. Journ. Sci.* quoted on p. 282, and his 'Characteristics.'

[2] E. Reyer (*Jahrb. Geol. Reichs.* 1879, p. 463) has experimentally imitated the process of extrusion by forcing up plaster of Paris through a hole in a board. See also E. Howe, *21st Ann. Rep. U. S. G. S.* part iii. (1901), p. 291. For drawings of the Puy de Sarcouy and other dome-shaped hills which presumably have had this mode of origin, see Scrope's 'Geology and extinct Volcanoes of Central France.' Refer also to the remarks already made on the liquidity of lava (*ante*, p. 301).

[3] *Ancient Volcanoes of Great Britain*, chaps. xlv.-xlvii.

[4] Stübel, 'Vulkanb. Ecuador,' p. 213.

Under the head of "Massive" or "Homogeneous" volcanoes some geologists have included the bosses or dome-like projections of once-melted rock which, in regions of extinct volcanoes, often rise conspicuously above the surface without any visible trace of cones or craters of fragmentary material. These have been regarded as protrusions of lava, which, like the trachytic Puys of Auvergne, assumed a dome-form at the surface without spreading out in sheets over the surrounding country, and with no accompanying fragmentary discharges. But the mere absence of ashes and scoriæ cannot be regarded as in itself an always reliable proof that these did not once exist, or that the present knob or boss of lava may not originally have solidified within a cone of tuff which has been subsequently removed in denudation. The extent to which the surface of the ground has been changed by ordinary atmospheric waste, and the comparative ease with

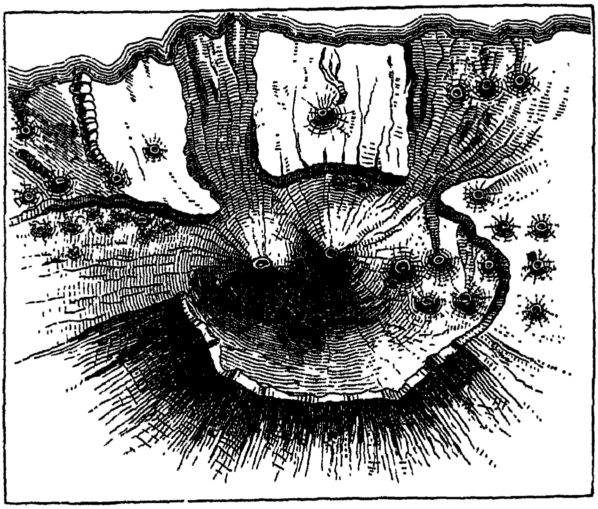

Fig. 60.—Plan of the Peak of Teneriffe, showing the large crater and minor cones.

which loose volcanic dust and cinders might have been entirely removed, require to be considered. Hence, though the ordinary explanation is no doubt in some cases correct, it may be doubted whether a large proportion of the examples cited from the Rhine, Bohemia, Hungary, and other regions, ought not rather to be regarded, like the "necks" so abundant in the ancient volcanic districts of Britain (Book IV. Part VII.), as the remaining roots of ordinary volcanic cones. If the tuff of a cone, up the funnel of which lava rose and solidified, were swept away, we should find a central lava plug or core resembling the volcanic "heads" (*vulkanische Kuppen*) of Germany. Unquestionably, lava has in innumerable instances risen in this way within cones of tuff or cinders, partially filling them without flowing out into the surrounding country.[1]

**6. Cones of Tuff and Lava.**—This is by far the most abundant type of volcanic structure, and includes most of the great volcanoes of the globe. Beginning, perhaps, as mere cones of fragmentary materials discharged by the first explosions, these eminences have gradually been built up by successive outpourings of lava from different sides, and by showers of dust and scoriæ. At first, the lava, if the sides of the cone are strong enough to resist its pressure, may rise until it overflows from the crater. Subsequently, as the funnel becomes choked up, and the cone is shattered by repeated explosions, the lava

[1] Von Seebach, *Z. D. G. G.* xviii. p. 643. F. von Hochstetter, *Neues Jahrb.* 1871, p. 469. Reyer, *Jahrb. K. K. Geol. Reichsanstalt*, 1887, p. 81; 1879, p. 463.

finds egress from different fissures and openings on the cone. As the mountain increases in height, the number of lava-currents from its summit will usually decrease. Indeed, the taller a volcanic cone grows, the less frequently as a rule does it erupt. The lofty volcanoes of the Andes have each seldom been more than once in eruption during a century. The peak of Teneriffe (Fig. 60) was three times active during 370 years prior to 1798.[1] The earlier efforts of a volcano tend to increase its height, as well as its

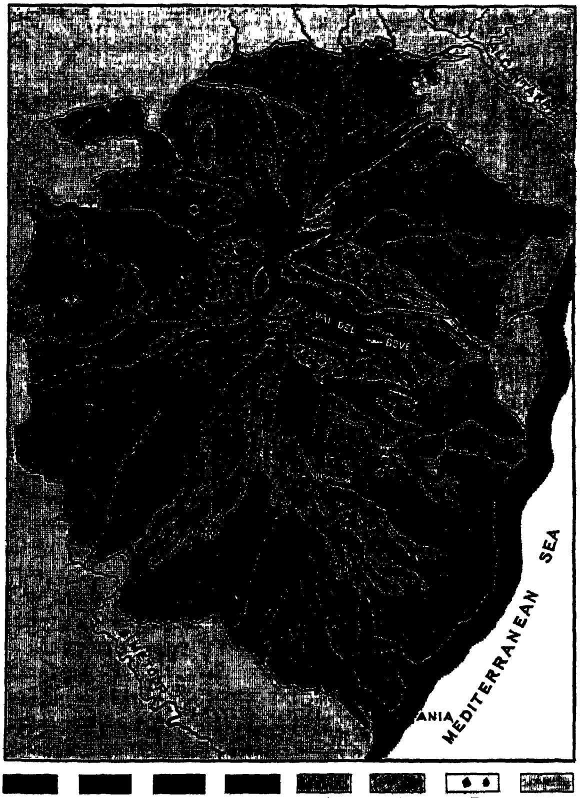


Fig. 61.—Map of Etna, after Sartorius von Waltershausen.
1, Lava of 1879; 2, Lavas of 1865 and 1852; 3, Lava of 1669; 4, Recent Lavas; 5, Lavas of the Middle Ages; 6, Ancient Lavas of unknown date; 7, Cones and Craters; 8, Non-volcanic Rocks.

breadth; the later eruptions chiefly augment the breadth, and are often apt to diminish the height by blowing away the upper part of the cone. The formation of fissures and the consequent intrusion of a network of lava-dykes tend to bind the framework of the volcano and strengthen it against subsequent explosions. In this way, a kind of oscillation is established in the form of the cone, periods of crater-eruptions being succeeded by others when the emissions take place only laterally (*ante*, p. 288).

One consequence of lateral eruption is the formation of minor parasitic cones on the flanks of the parent volcano (p. 326). Those on Etna, more than 200 in number, are really miniature volcanoes, some of them reaching a height of 700 feet (Fig. 61). As

[1] For a recent account of Teneriffe, see A. Rothpletz, *Petermann's Mittheil.* xxxv. (1889), p. 237.

the lateral vents successively become extinct, the cones are buried under sheets of lava and showers of débris thrown out from younger openings or from the parent cone. It sometimes happens that the original funnel is disused, and that the eruptions of the volcano take place from a newer main vent. Vesuvius, for example (as shown in Figs. 44 and 62), stands on the site of a portion of the rim of the more ancient and much larger vent of Monte Somma.[1] The present crater of Etna lies to the north-west of the former vaster crater. The pretty little example of such shifting of the eruptive orifice furnished by Vulcanello has been already noticed (p. 323).


Fig. 62.—Section of Vesuvius and Monte Somma from north to south.
*a*, Plain of the Campagna; *b*, Village of Somma (418 French feet); *c*, Fontana dell' Olivella (994); *d*, Casa Cancaroni (1588); *e*, Punta di Nasone (3430), on crest of old crater of Monte Somma; *f*, Atrio del Cavallo, bottom of old Crater of Monte Somma; *g*, *i*, edges of modern crater (*h*) of Vesuvius (3640); *k*, Boche Nuove (1515); *l*, Camaldoli (534); *m*, Torre dell' Annunziata, on Bay of Naples.

While, therefore, a volcano, and more particularly one of great size, throwing out both lava and fragmentary materials, is liable to continual modification of its external form, as the result of successive eruptions, its contour is likewise usually exposed to extensive alteration by the effects of ordinary atmospheric erosion, as well as from the condensation of the volcanic vapours. Heavy and sudden floods, produced by the rapid rainfall consequent upon a copious discharge of steam, rush down the slopes with such volume and force as to cut deep gullies in the loose or only partially consolidated tuffs and scoriæ. Ordinary rain continues the erosion until the outer slopes, unless occasionally renewed by fresh showers of detritus, assume the curiously trenched aspect already noticed, like that of a half-opened umbrella, the ridges being separated by furrows that narrow upwards towards the summit of the cone. The outer declivities of Monte Somma afford an excellent illustration of this form of surface, the numerous ravines on that side of the mountain presenting instructive sections of the pre-historic lavas and tuffs of the earlier and more important period in the history of this volcano.[2] Similar trenches have been eroded on the southern or Vesuvian side of the original cone, but these have in great measure been filled up by the lavas of the younger mountain. The ravines, in fact, form natural channels for the lava, as may unfortunately be seen round the Vesuvian observatory. This building is placed on one of the ridges between two deep ravines; but the lava-streams of recent years have poured into these ravines on either side, and are rapidly filling them up.

**Submarine Volcanoes.**[3]—It is not only on the

[1] Another huge volcano possessing much similarity in structure to Vesuvius is Monte Vulture, which lies to the east in the middle of the peninsula. Its structure has been well worked out by G. de Lorenzo, *Atti Accad Sci.*, Naples, x. (1900), p. 208; and a comparison between it and Vesuvius by the same writer will be found in *Rend. Accad. Sci.*, Naples, Nov. 1901.

[2] See H. J. Johnston-Lavis, *Q. J. G. S.* xl. (1884), p. 193. R. T. Günther on the denudation of the volcanic district of Camaldoli, *Geograph. Journ.* Nov. 1897.

[3] The known examples have been collected by E. Rudolph in his papers, "Ueber submarine Erdbeben und Eruptionen," *Beiträge zur Geophysik*, Leipzig, i. (1887), pp. 133-365 (especially pp. 226-250 and the map in Plate vii.); ii. (1895), pp. 537-666; iii. (1898),

surface of the land that volcanic action shows itself. It takes place likewise on a vast scale under the sea. As the geological records of the earth's past history are chiefly marine formations, the characteristics of submarine volcanic action have no small interest for the geologist. A few instances where the actual outbreak of a submarine eruption has been witnessed, or where the scene of the eruption was visited immediately after, may here be cited, together with some examples of the elevation of submarine volcanic accumulations and their dissection by the sea.

In the early summer of 1783, a volcanic eruption took place about thirty miles from Cape Reykjanaes on the west coast of Iceland. An island was built up, from which "fire and smoke" continued to issue, but in less than a year the waves had washed the loose pumice away, leaving a submerged reef from five to thirty fathoms below sea-level. About a month after this eruption, the frightful outbreak near Skaptar Jökull, already referred to (p. 300), began, the distance of this mountain from the submarine vent being nearly 200 miles.[1] A century afterwards, viz. in July 1884, another volcanic island is said to have been thrown up near the same spot, having at first the form of a flattened cone, but soon yielding to the power of the breakers. In May 1796, about 40 miles out in Bering Sea to the west of Unalaska, a volcano (Bogoslof) broke out with great violence, throwing stones as far as Umnak, a distance of 30 miles. The volcanic pile continued to increase in size until about 1823. At its maximum it is said to have reached a height of 2500 feet. But when its activity waned, it soon began to yield to the attacks of the climate and the sea. So rapid is the decay of the rock that when a rifle-shot was fired into a flock of sea-birds and caused them to rise, "small pieces of stone were detached, and in turn displaced larger pieces, until a perfect avalanche of stone came down the declivity, scoring great ruts in the hillside and tearing up great masses of stone, which were dashed to pieces on the shore below." Half a mile to the north-west a new volcano appeared, the actual outbreak of which was not seen, but which was first observed in full activity in September 1883. It is about 500 feet high, but its activity is lessening, and it appears to be diminishing in size. A picturesque stack called the Ship Rock, which once rose between the two volcanoes, but has been demolished by waves and weather, probably marked an earlier vent. A lateral shift of the funnel produced the Bogoslof volcano of 1796, while another alteration gave rise to a third volcano—the new Bogoslof of 1883. So powerful are the forces of denudation in this region, that unless the volcanic energy repairs the losses by piling up fresh material, the islands must before long disappear. The lava emitted here is a hornblende-andesite.[2]

Many submarine eruptions have taken place within historic times in the Mediterranean. The most noted of these occurred in the year 1831, when a new volcanic island (Graham's Island, Isola Ferdinandea, Ile Julia) was thrown up, with abundant discharge of steam and showers of scoriæ, between Sicily and the coast of Africa. It reached an extreme height of 200 feet or more above the sea-level (800 feet above sea-bottom), with a circumference of 3 miles, but on the cessation of the eruptions was attacked by the waves and soon demolished, leaving only a shoal to mark its site.[3] The island of Pantelleria to the south-west of Sicily is entirely of volcanic origin, but no eruptions were known to have occurred there in historic times, though hot springs

pp. 273-336 (a discussion of the effects of the explosion of torpedoes and mines under the sea).

[1] Lyell, 'Principles,' ii. p. 49.

[2] C. H. Merriam in 'Alaska—by the Harriman Expedition,' London, 1902, vol. ii. p. 291.

[3] W. H. Smyth, *Phil. Trans.* 1832. Constant Prévost, *Ann. des Sci. Nat.* xxiv. *Mém. Soc. Géol. France*, ii. p. 91. Mercalli's 'Vulcani, &c.' p. 117. A bibliography of Graham's Island is given in Dr. Johnston-Lavis' 'South Italian Volcanoes.'

exist, and also emanations of carbonic acid gas. During the summer of the year 1890 earthquakes began to be felt, but they ceased until 14th October 1891, when they began again with greater violence, and three days later a submarine eruption took place four miles to the north-west of the island. The sea was violently agitated, and covered with black scoriaceous bombs along a line one kilometre in length, on some parts of which the discharges were specially vigorous. The bombs exploded and ran hissing over the surface of the water with the recoil, but in eight days the eruption ended

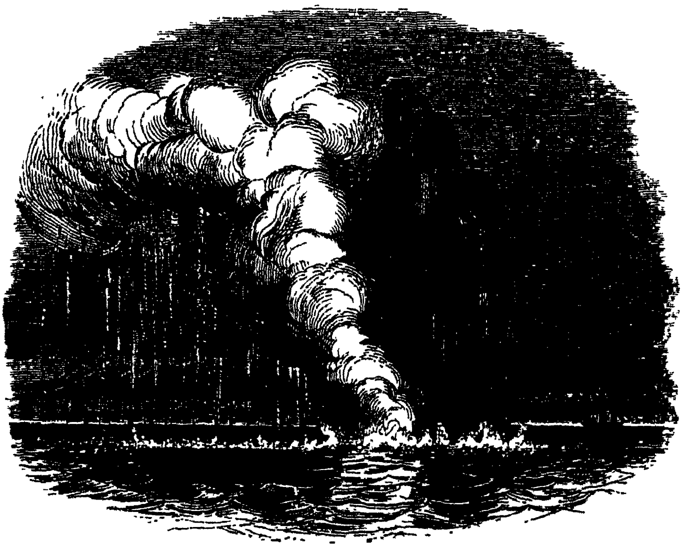

Fig. 63.—Sketch of submarine volcanic eruption (Sabrina Island) off St. Michael's, June 1811.

and the ejected material disappeared.[1] In the year 1811, another island was formed by submarine eruption off the coast of St. Michael's in the Azores (Fig. 63). Consisting, like the Mediterranean examples, of loose cinders, it rose to a height of about 300 feet, with a circumference of about a mile, but subsequently disappeared.[2]

In recent years various submarine eruptions have taken place in the Pacific Ocean. The history of one of these in the Friendly or Tonga group of islands has been given by Admiral Sir William Wharton.[3] In the year 1867 a shoal was reported 30 miles west of Nomuka Island in that group. In 1877 smoke was observed to be rising from the sea at the spot. In 1885 a volcanic island, which was named Falcon Island, rose from the sea during a submarine eruption on 14th October; it was reported by a passing steamer to be two miles long and about 250 feet high. Next year its length was estimated at rather less than a mile and a half, and its height at 165 feet, with a crater from which dense columns of smoke were rising. In 1889 it was carefully surveyed by Commander Oldham, R.N., of H.M.S. *Egeria*, who found it to be $1\frac{1}{10}$th mile long and $\frac{8}{10}$ths of a mile wide, and to slope upwards from a plain a little above the sea-level on the north side to a height of 153 feet, plunging thence in a line of cliff into the sea. Apparently composed of nothing but fragmentary materials, it was rapidly attacked by the waves, and while the survey was in progress continual landslips were taking place from the

[1] Riccò, *Compt. rend.* Nov. 1891. *Annal. Uff. Centr. Meteorol. e Geodynam.* ser. ii. part 3, vol. xi. G. W. Butler, *Nature*, xlv. (1891), pp. 154, 251, 584.

[2] De la Beche, 'Geological Observer,' p. 70.

[3] *Nature*, xli. (1890), p. 276; xlvi. (1892), p. 611; lix. (1899), p. 582.

face of the sea-washed precipice. A little steam issuing from cracks in the cliffs was the only sign of volcanic activity. In the autumn of 1892 it was found by a passing French war-vessel to be only 25 feet high. The place was again examined by an English surveying vessel in 1898, and the island was found to have disappeared, leaving only a shoal over which the waves were breaking.

Another example from the same region is supplied by the history of Metis Island, about 75 miles N.N.E. from Falcon Island. This volcanic islet was first noticed in 1875, when it was 25 feet high, which elevation was increased by subsequent eruptions to 150 feet, but in twenty-four years it had been washed away, leaving only a submerged bank in its place. In these instances the erupted materials consisted only of ashes and blocks, with no inner plug of lava which would have longer resisted the power of the waves.[1]

Among the numerous volcanic groups of islands in the Pacific Ocean no rocks of continental types have been found, though upraised coral-reefs are not infrequent round their coasts, and marine limestones, probably of Tertiary age, appear in some of them. A large number of these volcanic cones have been quiescent ever since their discovery. Many of them, however, have from time to time been in eruption, and some are constantly active. A remarkable chain of volcanic vents may be traced from the Santa Cruz Islands to the southern end of the New Hebrides group, a distance of 600 miles. Each of the islands appears to mark the position of a distinct volcanic orifice, round which solid materials have accumulated until they have risen to sometimes as much as 4755 feet above the sea (Lopevi). A few of them are active, and have been the scene of vigorous eruptions within the last century. One of these paroxysms has been above referred to (p. 308) as having taken place on Ambrym, New Hebrides, in October and November 1894. This island rises to a height of 4380 feet, but has originally been probably at least twice as high. Its central feature is a vast crater five to six miles in diameter, the bottom of which is a great plain of ashes about 2100 feet above sea-level, encircled by a continuous wall of rock from 100 to 200 feet high. This huge caldera has evidently been caused by some ancient explosion, whereby the upper half of the cone was blown away. Subsequently two minor vents have been opened within and on the rim of the original crater, and have each built up a lofty cone with a huge crater a mile in diameter. Signs of volcanic activity in this island have been recorded ever since the days of Captain Cook (1774). The last eruption, as we have seen, was fortunately witnessed by one of the surveying vessels of the British Navy stationed there at the time. With the accompaniment of continual earthquake shocks a vast amount of fine black dust was discharged into the air to a height of 26,000 feet; and though the lava rose up to the floor of the most westerly of the two great vents, it did not escape there, but found an exit from the side of the mountain many hundred feet lower in level and several miles away. The lava (augite-andesite) rushed down the wooded valley, setting fire to the brushwood, until it eventually reached the sea, into which it advanced for 170 yards, with a breadth of 30 yards. Immediately after the molten stream had entered the water a column of steam shot up from it to a height of 4600 feet. There was no explosion, but "enormous bubbles of water commenced to rise to some 50 or 100 feet, like the explosions of heavy submarine mines, and then burst violently outwards in radiating tongues and black masses of presumably lava." Large quantities of dead fish and an occasional turtle floated about off the point.[2]

[1] Sir W. Wharton, *Nature*, lix. (1899), p. 582. Mr. J. J. Lister has given an interesting account of the geology of the whole Tonga group, accompanied with a map on which the distribution of the volcanoes and islands of tuff is shown. He gives further particulars regarding Falcon Island, with the results of an examination of specimens of the lava-bombs by Mr. Harker, who found them to be basic augite-andesites. *Q. J. G. S.* xlvii. (1891), pp. 590-616.

[2] Commander H. E. Purey Cust, 'Report on the Eruption of Ambrym Island, New

By repeated eruptions the volcanic material may be heaped up to a height of many thousand feet. In Hawaii it has risen some 14,000 feet above the sea. From this extreme elevation successively lower levels have been reached until in many cases the volcanic cones have not risen out of the water. There is reason to believe that the hundreds of atolls or coral-islands so widely distributed over this ocean have been formed on the summits of submarine volcanic peaks (Book III. Part II. Sect. iii. § 3). Here and there, as will be further referred to in later pages, the submarine lavas and tuffs have been upraised, so that the foundations on which the coral reefs have been built can be studied.[1]

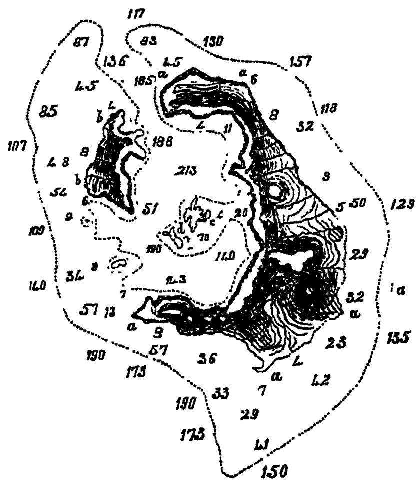

Fig. 64.—Map of partially submerged Volcano of Santorin.

*a*, Thera, or Santorin; *b*, Therasia; *c*, Mikro Kaimeni; *d*, Neo Kaimeni. The figures denote soundings in fathoms, the dotted line marks the 100 fathoms line.

Unfortunately, the phenomena of recent volcanic eruptions under the sea are for the most part inaccessible. Here and there, as in the Bay of Naples, at Etna, among the islands of the Greek Archipelago, at Tahiti and Christmas Island, in the Indian Ocean, elevation of the sea-bed has taken place, and brought to the surface beds of tuff or of lava which have consolidated under water. Both Vesuvius and Etna began their career as submarine volcanoes.[2] It will be seen from the accompanying chart (Fig. 64), that

Hebrides, S.W. Pacific, October and November 1894,' published by the Admiralty. While these pages are passing through the press, telegraphic information has arrived of another disastrous eruption in Tori Shima, one of the chain of volcanic islands which extends between the south end of Japan and the Bonin Isles. An eruption between the 13th and 15th August 1902 is said to have overwhelmed the island and all its inhabitants, together with their houses. A submarine vent had likewise opened near the island, and passing vessels found the place dangerous of approach.

[1] For a general account of the VOLCANIC ISLANDS of the ocean, see Darwin's 'Volcanic Islands,' 2nd. edit. 1876. For the Philippine volcanoes, see R. von Drasche, *Tschermak's Mineralogische Mittheil.* 1876; Semper's 'Die Philippinen und ihre Bewohner,' Würzburg, 1869; G. F. Becker, *20th Ann. Rep. U. S. G. S.* (1898-99), pp. 1-7; *21st Ann. Rep.* (1899-1900), pp. 487-547. For the Kurile Islands, J. Milne, *Geol. Mag.* 1879, 1880, 1881. Volcanoes of Bay of Bengal (Barren Island, &c.), V. Ball, *Geol. Mag.* 1879, p. 16; 1888, p. 404; 1893, p. 289; F. R. Mallet, *Mem. Geol. Surv. India*, xxi. part iv.; J. D. Dana, *Amer. Jour. Sci.* May 1886, p. 394. St. Paul (Indian Ocean), C. Vélain, *Assoc. Fran.* 1875, p. 581; 'Mission à l'Île St. Paul,' 1879; 'Description géologique de la Presqu'île d'Aden, &c.' 4to, Paris, 1878; and 'Les Volcans,' 1884. For Isle of Bourbon, see authorities cited on p. 323; and for Hawaii, the references on p. 282. New Hebrides, Captain Frederick, *Q. J. G. S.* xlix. (1893), p. 227. Fiji Islands, E. C. Andrews, *Bull. Mus. Comp. Zool.* xxxviii. (1900). West Indian Islands, the copious Reports of the various Commissions sent to investigate the disastrous eruptions of May 1902 in St. Vincent and Martinique, as that of the Royal Society, the National Geographic Society of Washington, and the Academy of Sciences of Paris. See also Grosser, *Verhandl. Natur. Ver. Preuss. Rheinl.* 1899; J. Stanley Gardiner, *Q. J. G. S.* liv. (1895), p. 1; and papers cited in Book III. Part II. Sect. iii. § 3, in the discussion of coral-reefs.

[2] See, as regards Etna, 'Der Aetna,' ii. p. 327.

the islands of Santorin and Therasia form the unsubmerged portions of a great crater-rim rising round a crater which descends 1278 feet below sea-level. The materials of these islands consist of a nucleus of marbles and schists, nearly buried under a pile of tuffs (trass), scoriæ and sheets of lava, the bedded character of which is well shown in the accompanying sketch by Admiral Spratt (Fig. 65), who, with Edward Forbes, examined the geology of this interesting district in 1841. They found some of the tuffs to contain marine shells, and thus to bear witness to an elevation of the sea-floor since volcanic action began. More recently the islands have been carefully studied by various observers. K. von Fritsch has found recent marine shells in many places up to heights of nearly 600 feet above the sea. The strata containing these remains he estimates to be at least 100 to 120 metres thick, and he remarks that in every case he found them to consist essentially of volcanic débris and to rest upon volcanic rocks. It is evident, therefore, that these shell-bearing tuffs were originally deposited on the sea-floor after volcanic action had begun here, and that during later times they were upraised, together with the submarine lavas associated with them.[1] Fouqué concludes that the volcano formed at one time a large island with wooded slopes and a somewhat civilised human population, cultivating a fertile valley in the south-western district, and that in prehistoric times the tremendous explosion occurred whereby the centre of the island was blown out.

The similarity of the structure of Santorin to that of Somma and Etna is obvious. Volcanic action still continues there, though on a diminished scale. In 1866-67 an

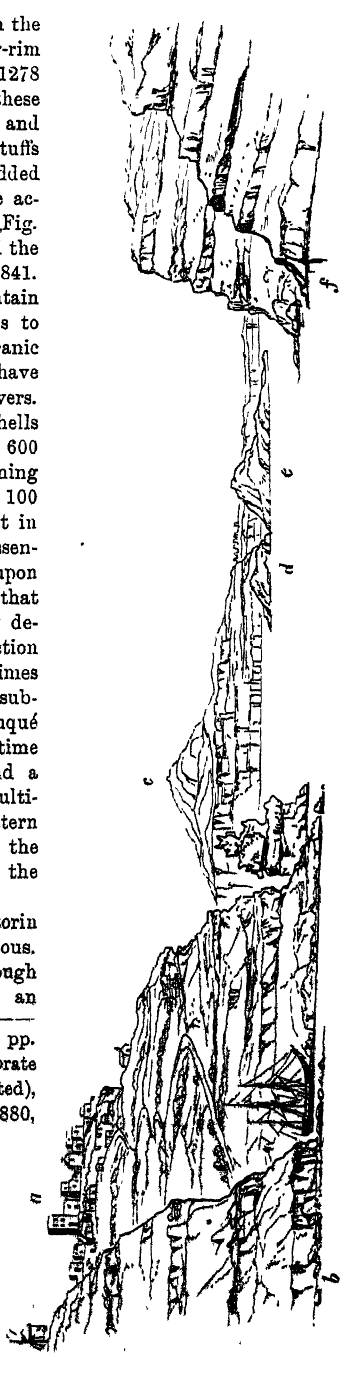


Fig. 65.—View of the interior of the crater of Santorin from the entrance.

a, Town of Apanomeria, standing on tuffs, &c.; b, North-west cape of Santorin, with bedded tuffs and lavas; c, Mount St. Elias (568 metres), consisting of marble, &c. (shown by oblique lines in the chart, Fig. 64), and forming with the surrounding district a non-volcanic tract in the midst of the lavas and tuffs; d, Mikro Kaimeni; e, Neo Kaimeni, the scene of the eruptions in 1866-67; f, Therasia, an island composed, like Santorin, of beds of tuff, slags, and lavas.

[1] See Fritsch, *Z. D. G. G.* xxiii. (1871), pp. 125-213. The most complete and elaborate work is Fouqué's monograph (already cited), 'Santorin et ses Éruptions,' Paris, 4to, 1880, where copious analyses of rocks, minerals, and gaseous emanations, with maps and numerous admirable views and sections, are given. In this volume a bibliography of the locality will be found. Compare C. Doelter on the Ponza Islands, *Denksch. Akad. Wissensch.*, Vienna, xxxvi. p. 141. *Sitz. Akad. Wissensch.*, Vienna, lxxi. (1875), p. 49.

eruption took place on Neo Kaimeni, one of the later-formed islets in the centre of the old crater, and greatly added to its area and height. The recent eruptions of Santorin, which have been studied in great detail, are specially interesting from the additional information they have supplied as to the nature of volcanic vapours and gases. Among these, as already stated (p. 268), free hydrogen plays an important part, constituting, at the focus of discharge, 30 per cent of the whole. By their eruption under water, the mingling of these gases with atmospheric air and the combustion of the inflammable compounds is there prevented, so that the gaseous discharges can be collected and analysed. Probably were operations of this kind more practicable at terrestrial volcanoes, free hydrogen and its compounds would be more abundantly detected than has hitherto been possible.

In the group of islands at the western side of the Bay of Naples a beautiful example of a volcanic islet is to be seen in the Isola di Vivara. It consists of a cone of breccias and tuffs. Only the western half of this cone remains prominently above water, the rest having been in great part washed away, though the circular rim of the crater can be traced in a line of low reefs, inside of which lies a sheltered basin filled by the sea. Excellent sections have been cut by the waves along the exposed side of the segment of the cone, showing the succession of fragmentary discharges composed of a commingling of trachytic and basaltic materials.[1]

The numerous volcanoes which dot the Pacific Ocean began their career as submarine vents, their eventual appearance as subaerial cones being mainly due to the accumulation of erupted material, but also partially, in at least their later stages, to actual upheaval of the sea-bottom. These features are impressively displayed among the Fiji Islands, where a succession of Tertiary limestones has been uplifted. These calcareous deposits are not coral-reefs, but have been formed by foraminifera, nullipores, polyzoa, shells, and echinoderms. They are overlain with fossiliferous tuffs, volcanic conglomerates, and a peculiar volcanic mudstone known locally as "soapstone," which shows gradations from an ordinary submarine tuff to an ashy foraminiferal rock. Next in order come limestones, which consist partly of reef-coral, which is especially seen as a capping about 100 feet thick. Much of this limestone has been elevated from 800 to 1050 feet above the sea. Above it lie agglomerates of andesite and coral-rock, some of the limestone blocks being 4 or 5 feet in diameter. Massive flows of andesite-lava have been poured out upon these agglomerates, rising into dome-shaped eminences sometimes 700 feet high and attaining a thickness of about 300 feet. The youngest volcanic ejections appear to be some small protrusions of basalt. A late movement of elevation has carried a former sea-beach up to above 50 feet above sea-level.[2]

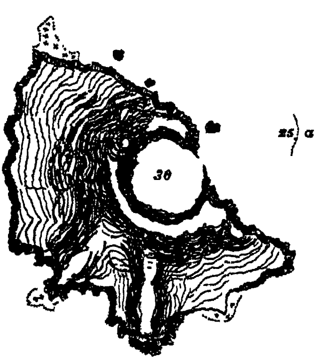

Fig. 66.—Volcanic crater of St. Paul Island, Indian Ocean.

The lonely island of St. Paul (Figs. 66 and 68), lying in the Indian Ocean more than 2000 miles from the nearest land, is a notable example of the summit of a volcanic mountain rising to the sea-level in mid-ocean. Its circular crater, broken down on the north-east side, is filled with water, having a depth of 30 fathoms. Christmas Island, in the same ocean, already referred to, is another remarkable example of a volcanic

[1] This island, its petrography and structure, have been well described by G. de Lorenzo and C. Riva in their memoir, "Il Cratere di Vivara," cited *ante*, p. 290.

[2] E. C. Andrews, *Bull. Mus. Comp. Zool.* xxxviii. (1900), with preface by Professor Edgeworth David, p. 5.

mountain rising from a depth of more than 14,000 feet to a height of 1100 feet above sea-level. Its latest lavas and tuffs are intercalated among the upraised Tertiary and younger limestones that were laid down on the summit of the peak, and have since been uplifted into land. The oldest lavas are trachytic and the latest basaltic in character. Some of the sheets of basalt have broken up under water, and their crevices are filled with volcanic detritus mingled with foraminifera and other marine organisms. The tuffs are palagonitic, in beds 50 feet thick, with foraminifera scattered through them. Among the detrital masses are sheets of volcanic conglomerate.[1]

Observations by R. von Drasche have shown that at Bourbon (Réunion), during the early submarine eruptions of that volcano, coarsely crystalline rocks (gabbro) were emitted; that these were succeeded by andesitic and trachytic lavas; but that when the vent rose above the sea, basalts were poured out.[2] Fouqué observes that at Santorin, while some of the early submarine lavas are identical with those of later subaerial origin, the greater part of them belong to an entirely different series, being acid rocks, referable to the group of hornblende-andesites, while the subaerial rocks are augite-andesites. The acidity of these lavas has been largely increased by the infusion into them of silica, chiefly in the form of opal. They vary much in aspect, being sometimes compact, scoriaceous, hard, like millstone, with perlitic and spherulitic structures, while they frequently present the characters of trass impregnated with opal and zeolites. Among the fragmental ejections there occur blocks of schist and granitoid rocks, probably representing the materials below the sea-floor through which the first explosion took place (pp. 275, 291, 292, 326). During the eruption of 1866 some islets of lava rose above the sea in the middle of the bay, near the active vent. The rock in these cases was compact, vitreous, and much cracked.[3]

Among submarine volcanic formations, the tuffs differ from those laid down on land chiefly in their organic contents; but partly also in their more distinct and originally less inclined bedding, and in their tendency to the admixture of non-volcanic or ordinary mechanical sediment with the volcanic dust and stones. No appreciable difference either in external aspect or in internal structure seems yet to have been established between subaerial and submarine lavas. Some undoubtedly submarine lavas are highly scoriaceous. There is no reason, indeed, why slaggy lava and loose, non-buoyant scoriæ should not accumulate under the pressure of a deep column of the ocean. At the Hawaiian Islands, on 25th February 1877, masses of pumice, during a submarine volcanic explosion, were ejected to the surface, one of which struck the bottom of a boat with some violence and then floated (*postea*, p. 353). When we reflect, indeed, to what a considerable extent the bottom of the great ocean-basins is dotted over with volcanic cones, rising often solitary from profound depths, we can believe that a large proportion of the actual eruptions in oceanic areas may take place under the sea. The immense abundance and wide diffusion of volcanic detritus (including blocks of pumice) over the bottom of the Pacific and Atlantic Oceans, even at distances remote from land, as made known by the voyage of the *Challenger*, doubtless indicate the prevalence and persistence of submarine volcanic action, even though, at the same time, an extensive diffusion of volcanic débris from the islands is admitted to be effected by winds and ocean-currents.

Volcanic islands, unless continually augmented by renewed eruptions, are attacked by the waves and cut down. Graham's Island and the other examples above cited show how rapid this disappearance may be. The island of Vulcano has the base of its slopes truncated by a line of cliff due to marine erosion. The island of Teneriffe shows, in the same way, that the sea is cutting back the land towards the great cone (Fig. 67). The

[1] C. W. Andrews, 'Christmas Island, Indian Ocean,' published by British Museum, 1900.

[2] *Tschermak's Mineralogische Mittheil.* 1878, pp. 42, 159. A similar structure occurs at Palma (Cohen, *Neues Jahrb.* 1879, p. 482) and in St. Paul (Vélain as above cited).

[3] Fouqué, 'Santorin.'

island of St. Paul (Figs. 66, 68) brings before us in an impressive way the tendency of volcanic islands to be destroyed unless replenished by continual additions to their

Fig. 67.—View of the Peak of Teneriffe and its coast-erosion.

surface. At St. Helena lofty hills of volcanic rocks 1000 to 2000 feet high bear witness to the enormous denudation whereby masses of basalt two or three miles long, one or two miles broad, and 1000 to 2000 feet thick, have been entirely removed.[1]

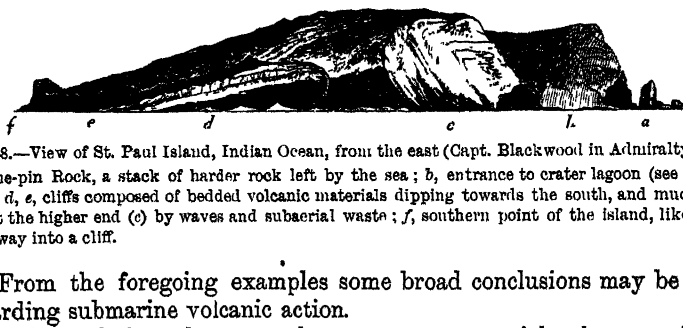


Fig. 68.—View of St. Paul Island, Indian Ocean, from the east (Capt. Blackwood in Admiralty Chart). *a*, Nine-pin Rock, a stack of harder rock left by the sea; *b*, entrance to crater lagoon (see Fig. 66); *c*, *d*, *e*, cliffs composed of bedded volcanic materials dipping towards the south, and much eroded at the higher end (*c*) by waves and subaerial waste; *f*, southern point of the island, likewise cut away into a cliff.

From the foregoing examples some broad conclusions may be drawn regarding submarine volcanic action.

1. It is obvious that not only are most terrestrial volcanoes situated near to the sea, but that volcanic activity is displayed over a wider region of the ocean floor than over the surface of the land, and on a more gigantic scale. We have only to turn to a chart of the Pacific Ocean, and note the numerous groups and chains of islands, in order to realise the wide extent and great vigour of submarine eruptions. Each of these islands marks the site of a volcanic cone gradually built up from the sea-bottom by successive outpourings of material. The Atlantic Ocean offers similar though less striking evidence in the same direction. The

[1] Darwin, 'Volcanic Islands,' p. 104. For a more detailed account of this island, see J. C. Melliss' 'St. Helena,' London, 1875.

scattered islands from Jan Mayen and Iceland southwards by the Azores, Canary, and Cape Verd Islands to the far distant Tristan d'Acunha and the Antarctic volcanoes, and again the chain of the Antilles on the western side, afford an impressive picture of volcanic energy. In estimating the bulk of the oceanic volcanoes, we must remember the profound depths from which many of them rise. An islet which only just shows itself above sea-level must often be the summit of a cone which would be reckoned among the more colossal volcanoes of the globe if it stood on the land. Christmas Island, in the Indian Ocean, the crest of which is 1100 feet above the sea, is really a mountain 15,500 feet high, rising from one of the oceanic abysses. Still more gigantic is the volcanic ridge of the Sandwich Islands, which has been built up from a depth of more than 18,000 feet to a height of nearly 14,000 feet above sea-level, thus forming a volcanic chain higher than even the highest peak of the Himalayas, and still continuing to erupt from its crest.

2. Submarine eruptions, so far as the available evidence warrants any inference, appear to build up conical volcanoes rather than to form wide plateaux. They tend to occur along tolerably well-marked lines, as well as in scattered groups. The linear direction is strikingly shown by such chains as the Aleutian Islands, Japan, Java, and the Antilles. Along these lines, which are usually looked upon as marking fissures in the terrestrial crust, volcanic cones have been built up, sometimes set close together, sometimes many miles apart. As a rule these cones have come into existence in succession, some dying out and others still continuing. Thus along the great volcanic ridge of the Sandwich Islands, as Dana has pointed out, fifteen volcanoes of the first class have been active, but all of them, save three in Hawaii, appear to be now extinct.

3. From the evidence supplied by lavas which were originally poured out under the sea, but have subsequently been upraised above its level, and likewise by bombs that have been projected to the surface of the water during submarine eruptions, it may be concluded that molten material which has been erupted and has solidified beneath the waves does not materially differ in structure from that which comes from terrestrial vents. This inference has an important bearing on the study of ancient volcanic ejections, a large proportion of which, intercalated among marine sediments, must have been submarine. In particular, the cellular or amygdaloidal structure and microscopic characteristics, such as are seen in rocks like trachyte and basalt, are as well defined among submarine as among terrestrial volcanic products.

4. Such instances as have been observed of upraised submarine volcanic ejections show that lavas, tuffs, and breccias are interstratified among limestones formed of organic remains. It is evident that between the successive eruptions pauses took place, during which the organisms of the sea flourished abundantly and furnished materials for foraminiferal or radiolarian ooze, shell-banks, or coral-reefs. There can be little doubt that many of the sub-oceanic volcanic cones are of great antiquity, going back perhaps far into Tertiary times. They are thus probably built up of a succession of volcanic and organic accumulations. If it were possible to

examine this succession, it would reveal the stages of the volcanic history and the remains of the successive faunas that have come and gone while that history has been in progress.

### ii. *Fissure (Massive) Eruptions.*

From the position of Etna and Vesuvius in the centre of the early civilisation of Europe, these volcanoes came to be taken as the accepted types of volcanic structure and activity. It is now known, however, that they do not represent all forms of volcanic action. We have seen that the puys of Auvergne, and still more the great volcanoes of South America, bring before us another type where lava has been protruded in masses to the surface without the formation of the normal volcanic crater. But the most gigantic displays of subterranean energy are manifested by yet another type of eruption, where lava flows out from fissures which reach the surface, spreading sometimes over areas hundreds of miles in extent. Such fissure-eruptions have been chiefly exhibited in historic times in Iceland. Large tracts of that island have been rent by fissures, of which two systems are specially marked, one directed from S.W. to N.E. and the other from S. to N. The eruptions of Hekla and Laki belong to the former series. A violent eruption at Askya in 1875 took place at the intersection of two lines of fissures, some of which could be traced for nearly 50 English miles. Sometimes the fissure remains as an open chasm 600 feet or more in depth, without ejecting any volcanic material; in other cases it becomes the scene of intense volcanic activity, when lava rises in it and flows out tranquilly on either side, sometimes forming a row of cones of slag along the line of the chasm or a long rampart of slags and blocks piled up on either side. The great eruption of 1783 issued from the Laki fissure, about 20 miles long (Fig. 69), and poured forth in two vast floods, of which the western branch flowed for upwards of 40 miles and the other 28 miles. Hundreds of slag-cones were formed along the line of the fissure, varying in size from a couple of yards up to seldom more than 50 yards in height. Each cone might send out two or more streams of molten lava, now to one side, now to another, which merged into each other so as to flow round the cones and spread out into wide floods of black rock. So insignificant are these hillocks that in a rugged volcanic landscape they might not attract attention, yet they mark the source whence milliards of cubic yards of lava issued.

On level ground the Icelandic lava, which is remarkably liquid, spreads out as a wide floor of bare rock. Such is the great lava-desert of Odádahraun, which has an area of about 1700 English square miles. Where the ground is inclined,

Fig. 69.—Plan of small craters along the great Laki fissure of 1783, Iceland (after Mr. Helland, reduced).

the lava may flow to a great distance, filling up valleys and spreading over the lower country. One of the prehistoric lavas from Trölladyngjá in Odádahraun flowed for more than 60 miles. A succession of eruptions piles up a series of lava-sheets more or less nearly horizontal, which are eventually cut into ravines by the descending rivers.

In some parts of Iceland the lava has been built up into vast flat domes like those of Hawaii (*ante*, p. 328), having a gentle inclination in every direction. The highest of these are 1209 and 1491 metres high by from 6 to 15 kilometres in diameter. An elliptical crater on the loftiest dome measures 1100 by 380 metres. The Vesuvian type of cone built up of alternating lavas and tuffs is also to be found in Iceland under the snow-fields and ice-sheets; such are Öræfajökull (6241 feet), Eyjafjallajökull (5432), and Snaefellsjökull (4577). The mountain Hekla (4961), which is popularly believed to be the chief Icelandic volcano, is made up of successive sheets of lava and tuff, which, however, have not been formed into a cone but into an oblong ridge, fissured in the direction of its length and bearing a row of craters along the fissure.

While the outflow of lava may not be attended with violent eruptive energy, explosion-craters show that in Iceland, too, the pent-up internal gases and vapours sometimes manifest great vigour. One of these craters was formed at Askja, on 29th March 1795, by a tremendous explosion which scattered pumiceous stones over an area of more than 468 English square miles and discharged a vast amount of fine dust, some of which was carried as far as Norway and Sweden. Yet the opening then made has a diameter of only about 280 feet. Round the Icelandic explosion-craters the rim of fragmentary material is very little higher than the adjacent ground. Great though the amount of ejected stones and dust must be, it seems to be scattered with such force that only a small part of it falls back around the orifice.[1]

In former geological ages, extensive eruptions of lava, without the accompaniment of scoriæ, with hardly any fragmentary materials, and with, at the most, only flat dome-shaped cones at the points of emission, have taken place over wide areas from scattered vents, along lines or systems of fissures. Vast sheets of lava have in this manner been poured out to a depth of many hundred feet, completely burying the previous surface of the land and forming wide plains or plateaux. These truly "massive eruptions" have been held by Richthofen[2] and others to represent the grand fundamental character of volcanism, ordinary volcanic cones being regarded merely as parasitic excrescences on the subterranean lava-reservoirs, very much in the relation of minor cinder-cones to their parent volcano,[3] or of the lava-spiracles on the surface of a lava-stream (Figs. 48, 49).

[1] See the papers of Dr. Thoroddsen and Mr. Helland quoted on p. 277, and the summary of their observations in 'Ancient Volcanoes of Great Britain,' vol. ii. chap. xl.; also W. L. Watts' "Across the Vatna Jökull," *Proc. Roy. Geog. Soc.* 1876; W. G. Lock, *Geol. Mag.* 1881, p. 212; J. H. Johnston-Lavis, *Scottish Geograph. Mag.* Sept. 1895.

[2] *Trans. Acad. Sci. California*, 1868.

[3] *Proc. Roy. Phys. Soc. Edin.* v. 236; *Nature*, xxiii. p. 3.

Though a description of these old fissure or massive eruptions ought properly to be included in Book IV., the subject is so closely connected with the dynamics of existing active volcanoes that an account of the subject may be given here. The most stupendous example of this type of volcanic structure occurs in Western North America. The extent of country which has been flooded with basalt in Oregon, Washington, California, Idaho, and Montana has not yet been accurately surveyed, but has been estimated to cover a larger area than France and Great Britain combined.[1] The Snake River plain in Idaho (Fig. 70) forms part of

Fig. 70.—View of the great Basalt-plain of the Snake River, Idaho, with recent cones.

this lava-flood. Surrounded on the north and east by lofty mountains, it stretches westward as an apparently boundless desert of sand and bare sheets of black basalt. A few streams descending into the plain from the hills are soon swallowed up and lost. The Snake River, however, flows across it, and has cut out of its lava-beds a series of picturesque gorges and rapids. Looked at from any point on its surface, it appears as a vast level plain like that of a lake-bottom, though more detailed examination may detect a slope in one or more directions, and may thereby obtain evidence as to the sites of the chief openings from which the basalt was poured forth. The uniformity of surface has been produced either by the lava flowing over a plain or lake bottom, or by the complete effacement of an original and undulating contour of the ground under hundreds of feet of volcanic rock in successive sheets. The lava rolling up to the base of the mountains has followed the sinuosities of their margin, as the waters of a lake follow its promontories and bays. The author crossed the Snake River plain in 1879, and likewise rode for many miles along its northern edge. He found it to be everywhere marked with low hummocks or ridges of bare black basalt, the surfaces of which exhibited

[1] J. LeConte, *Amer. Journ. Sci.* 3rd ser. vii. (1874), pp. 167, 259.

a reticulated pavement of the ends of columns. In some places, there was a perceptible tendency in these ridges to range themselves in one general north-easterly direction, when they might be likened to a series of long, low waves, or ground-swells. In many instances the crest of each ridge had cracked open into a fissure which presented along its walls a series of tolerably symmetrical columns (Fig. 70). That these ridges were original undulations of the lava, and had not been produced by erosion, was indicated by the fact that the columns were perpendicular to their surface, and changed in direction according to the form of the ground which was the original cooling surface of the lava. Though the basalt was sometimes vesicular, no layers of slag or scoriæ were anywhere observed, nor did the surfaces of the ridges exhibit any specially scoriform character.

There are no great cones whence this enormous flood of basalt could have flowed. It probably escaped from orifices or fissures still concealed under the sheets which issued from them, the points of escape being marked only by such low domes as could readily be buried under the succeeding eruptions from other vents.[1] That it was not the result of one sudden outpouring of rock is shown by the distinct bedding of the basalt, which is well marked along the river ravines. It arose from what may have been, on the whole, a continuous though locally intermittent welling-out of lava, probably from vents on many fissures extending over a wide tract of Western America during a late Tertiary period, if, indeed, the last eruptions of this vast region did not come within the time of the human occupation of the continent.[2] The discharge of lava continued until the previous topography was buried under some 2000 feet (but in places as much as 3700 feet) of lava, only the higher summits still projecting above the volcanic flood.[3] At a few points on the plain and on its northern margin, the author observed some small cinder-cones (Fig. 70). These were evidently formed during the closing stages of volcanic action.

In Europe, during older Tertiary time, similar enormous outpourings of basalt covered many hundreds of square miles. The most important of these is that which occupies a large part of the north-east of Ireland, and in disconnected areas extends through the Inner Hebrides and the Faroe Islands into Iceland. Throughout that region, the paucity of evidence of volcanic vents is remarkable, though a few have been laid open by the sea in the coast-cliffs of the west of Scotland and the Faroes. So extensive has been the denudation, that the inner structure of the volcanic plateaux

[1] Captain Dutton has remarked the absence of any conspicuous feature at the sources from which some of the largest lava-streams of Hawaii have issued.

[2] In Northern California an example of the latest phase of eruption is seen at Cinder Cone, ten miles north-east from Lassen Peak. The lava there is so recent that some of the trees which it pushed over are still standing. From the age of some younger trees that have sprung up on the lava the date of its flow must have been at least 50 years before 1891, but may not have been much more. No record or tradition, however, either among the white settlers or the Indians, has survived of the actual eruption. J. S. Diller, *B. U. S. G. S.* No. 79 (1901).

[3] Professor J. LeConte believed that the chief fissures opened in the Cascade and Blue Mountain Ranges. *Amer. Journ. Sci.* 3rd series, vii. (1874), p. 168.

has been admirably revealed, showing that the ground beneath and around the basalt-sheets has been rent into innumerable fissures which have been filled by the rise of basalt into them. A vast number of basalt-dykes ranges from the volcanic area eastwards across Scotland, the north of England, and the north of Ireland. Towards the west the molten rock reached the surface and was poured out there in successive sheets to a depth of more than 3000 feet, while to the eastward it does not appear to have overflowed, or, at least, all evidence of the outflow has been removed in denudation. When we reflect that this system of dykes can be traced from the Orkney Islands southwards into Yorkshire and across Britain from sea to sea, over a total area of probably not less than 40,000 square miles, we can in some measure appreciate the volume of molten basalt which in older Tertiary times underlay large tracts of the site of the British Islands, rose up in so many thousands of fissures, and poured forth at the surface over so wide an area in the north-west.[1] The occurrence of layers of sedimentary material, including coal and leaf beds, with well-preserved terrestrial vegetation between some of the basalt-sheets, shows that considerable intervals sometimes occurred between successive outflows of lava.

In Africa, basaltic plateaux cover large tracts of Abyssinia, where by the denuding effect of heavy rains they have been carved into picturesque hills, valleys and ravines.[2] In India, an area of at least 200,000 square miles is covered by the singularly horizontal volcanic plateaux of the "Deccan Traps" (lavas and tuffs), which belong to the Cretaceous period and attain a thickness of 6000 feet or more.[3] The underlying platform of older rock, where it emerges from beneath the edges of the basalt tableland, is found to be in many places traversed by dykes ; but no cones and craters are anywhere visible. In these, and probably in many other examples still undescribed, the formation of great plains or plateaux of level sheets of lava is to be explained by "fissure-eruptions" rather than by the operations of volcanoes of the familiar "cone and crater" type.

## § 4. Geographical and geological distribution of volcanoes.

For an adequate conception of the distribution of volcanic action over the globe, account ought to be taken of dormant and extinct volcanoes, likewise of the proofs of volcanic outbreaks during earlier geological periods. When this is done, we learn that innumerable districts have been the scene of prolonged volcanic activity, where there is now no underground commotion ; that volcanic outbursts have been apt to take place again and again after wide intervals on the same ground, some modern active volcanoes being thus the descendants and representatives of older ones ; and that there are wide regions which from remote geological periods have been entirely unvisited by volcanic manifestations. Some of the facts regarding former volcanic action have been already stated. Others will be given in Book IV. Part VII.

Confining attention to vents now active, of which the total number has been computed to be about 300 or 400,[4] the chief facts regarding

[1] A. G., *Trans. Roy. Soc. Edin.* xxxv. (1888), p. 21 ; 'Ancient Volcanoes of Great Britain,' chaps. xxxiii. to xli. [2] Blanford's 'Abyssinia,' 1870, p. 181.

[3] Medlicott and Blandford, 'Geology of India,' 2nd edit. by R. D. Oldham, 1893, chap. xi. ; G. T. Clark, *Q. J. G. S.* xxv. (1869), p. 163.

[4] This number is probably considerably below the truth. Professor J. Milne has enumerated in Japan alone no fewer than fifty-three volcanoes which are either active or have been active within a recent period. He mentions the occurrence of 100 active vents from the Kuriles to Kinshu (2000 miles). He remarks that, "if we were in a position to indicate

their distribution over the globe may be thus summarised :—(1) Volcanoes occur along the margins of the ocean-basins, particularly along lines of dominant mountain-ranges, which either form part of the mainland of the continents or extend as adjacent lines of islands. The vast hollow of the Pacific is girdled with a wide ring of volcanic foci. (2) Volcanoes rise, as a striking feature, from the submarine ridges that traverse the ocean basins. All the oceanic islands are either volcanic or formed of coral, and the scattered coral-islands have in all likelihood been built upon the tops of submarine volcanic cones. (3) Volcanoes are generally situated not far from the sea or from some inland sheet of water. The only known exceptions to this rule are certain vents in Mantchouria and in the tract lying between Thibet and Siberia; but of the actual nature of these vents very little is yet known. (4) The prevalent arrangement of volcanoes is in series along what have probably been lines of dominant movement in the earth's crust, such as fracture or plication. This linear arrangement is conspicuous in the chain of the Andes, the Aleutian Islands, and the Malay Achipelago. A remarkable zone of volcanic vents girdles the globe from Central America eastward by the Azores, Cape Verd, and Canary Islands to the Mediterranean, thence to the Red Sea, and through the chains of islands from the south of Asia to New Zealand and the heart of the Pacific. (5) On a smaller scale, the distribution in long lines gives place to one in groups, as in Italy, Iceland, and the sporadic volcanic islands of the great oceans.

It is in the region of the Pacific Ocean that volcanic vents are most abundantly distributed. On the western side of this vast basin it has been estimated that there are 102 active vents, but the true number is probably much higher. On the eastern side the number is given as 113. The linear grouping of these volcanoes along the border of the Asiatic mainland extends through Kamtschatka, the Kurile Isles and Japan, southwards to the Malay Archipelago. In Sumatra, Java and the adjoining islands no fewer than fifty vents are placed, and the series is prolonged through New Guinea into New Zealand. More impressive still is the volcanic band which runs along the whole length of the American Continent. Even in the centre of this great ocean volcanic energy manifests itself on a colossal scale in the great lava-cones of the Sandwich Islands. The Atlantic Ocean includes some thirty volcanoes either now or lately active. Some of these rise from the great central ridge of this long oceanic trough in the Azores, Canary Islands and the degraded volcanoes of St. Helena, Ascension and Tristan d'Acunha, while others are grouped near the American and African borders, and those of Iceland rise from the ridge that separates the Atlantic and Arctic basins. In the Arctic Ocean lies the solitary Jan Mayen, while on the Antarctic Continent the giant Mounts Erebus and Terror tower above the ice-field. In the Indian Ocean five volcanoes appear, the number assigned to the continent of

the volcanoes which had been in eruption during the last 4000 years, the probability is that they would number several thousands rather than four or five hundred." 'Earthquakes and other Earth-movements,' 1886, p. 227. Compare Fisher, 'Physics of the Earth's Crust,' 2nd ed. chap. xxiv.

Asia is twelve, to Africa twenty-seven, while Europe has its four volcanic districts of Etna, Vesuvius, the Lipari Islands and Santorin.

Besides the existence of extinct volcanoes which have obviously been active in comparatively recent times, the geologist can adduce proofs of the former presence of active volcanoes in many countries where cones, craters and all the ordinary aspects of volcanic mountains have long disappeared, but where sheets of lava, beds of tuff, dykes and necks representing the sites of volcanic vents have been recognised abundantly (Book IV. Part VII.). These manifestations of volcanic action, moreover, have as wide a range in geological time as they have in geographical area. Every great geological period, back into pre-Cambrian time, seems to have had its volcanoes. In Britain, for instance, there were probably active volcanic vents in pre-Cambrian ages. The Archæan gneiss of N.-W. Scotland includes a remarkable series of dykes presenting some points of resemblance to the great system which afterwards appeared in Tertiary time. The Torridon sandstone of the same region, which is now known to be pre-Cambrian, contains pebbles of various finely vesicular rocks, such as might have come from volcanic eruptions. In the lower Cambrian period came the tuffs and diabases of Pembrokeshire. Still more vigorous were the volcanoes in the Lower Silurian period, when the lavas and tuffs of Snowdon, Aran Mowddwy and Cader Idris were ejected. During the deposition of the Upper Silurian rocks a few volcanoes were active in the south-west of England and the west of Ireland. The Lower Old Red Sandstone epoch was one of prolonged activity in Central Scotland, and to a less extent in the south of England. The earlier half of the Carboniferous period likewise witnessed great volcanic energy over the south of Scotland, and in a minor degree in central and south-western England and western Ireland. Lavas (andesites and trachytes) were then poured out in wide level plateaux from many vents for hundreds of square miles in the southern half of Scotland, while groups of minor cones, like the puys of Auvergne, were dispersed over the sea-floor and among the lagoons. During Permian time, more than a hundred small vents rose in scattered groups across the centre and south-west of Scotland, while a few similar points of eruption appeared in the south-west of England. No trace of any British Mesozoic volcanoes has been met with. The vast interval between Permian and older Tertiary time appears to have been a period of total quiescence of volcanic activity. The early Tertiary ages were distinguished by the outpouring of the enormous basaltic plateaux of Antrim and the Inner Hebrides.[1]

In France and Germany, likewise, Palæozoic time was marked by the eruption of many diabase, andesite, and quartz-porphyry lavas. In Brittany, for example, Dr. Barrois has found a remarkable series of older Palæozoic diabases and porphyrites with tuffs and agglomerates. He distinguishes four principal periods of eruption: (1) Cambrian and Lower Silurian; (2) Middle and Upper Silurian; (3) Upper Devonian;

[1] For a detailed summary of the volcanic history of Britain, see Presidential Addresses to the Geological Society, *Q. J. G. S.* xlvii. xlviii. (1891-92), and 'Ancient Volcanoes of Great Britain.'

(4) Carboniferous.[1] The Permian period was marked in Germany and also in the south of France by the discharge of great masses of various quartz-porphyries. The Triassic period likewise witnessed numerous eruptions. But from that period onward the same remarkable quiescence appears to have reigned all over Europe, which characterised the geological history of Britain during Mesozoic time.[2] In the Tertiary periods a prodigious outpouring of lavas, both acid and basic, continued from the Miocene epoch down even perhaps to the historic period. Examples of this great series are met with in Central France, the Eifel, Italy, Bohemia, and Hungary, almost to the existing period. Recent research has brought to light evidence of a long succession of Tertiary and post-Tertiary volcanic outbursts in Western America (Nevada, Oregon, Idaho, Utah, &c.). Volcanic rocks are associated with Palæozoic, Secondary, and Tertiary formations in New Zealand, where volcanic action is not yet extinct.

Thus it can be shown that, within the same comparatively limited geographical space, volcanic action has been rife at intervals during a long succession of geological ages. Even round the sites of still active vents, traces of far older eruptions may be detected, as in the case of the existing active volcanoes of Iceland, which rise from amid Tertiary lavas and tuffs. Volcanic action, which now manifests itself so conspicuously along certain lines, seems to have continued in that linear development for protracted periods of time. The actual vents have changed, dying in one place and breaking out in another, yet keeping on the whole along the same tracts. Taking all the manifestations of volcanic action together, both modern and ancient, we see that the subterranean forces have operated along great lines in the earth's crust, that they have again and again been active over regions which now lie far within the borders of the great continents, that the existing volcanoes form but a small proportion of the total number which have once flourished, and that certain regions, like most of European Russia, furnish no evidence of ever having possessed active volcanoes within their bounds.

**Sequence of Petrographic Types at Volcanic Vents.**—Reference may here be made to a feature of volcanic eruptions which will be more satisfactorily discussed in a later part of this text-book. From observations made in all parts of the world it has now been ascertained that in the life of each volcano a gradual change can be recognised in the chemical and mineralogical character of the materials which it discharges at the surface. The oldest lavas, whether erupted in streams above ground or expelled in dust and fragments, differ from those of middle age, and these again from those that belong to the closing epochs of activity. From researches made by him in Hungary, in China and in the western regions of the United States, Baron F. von Richthofen as far back as 1868 announced

[1] *Bull. Carte Géol. Détaill. France*, No. 7, 1889.

[2] Some trifling exceptions to this general statement are said to occur. C. E. M. Rohrbach describes Cretaceous teschenites and diabases in Silesia (*Tschermak's Min. Mittheil.* vii. (1885), p. 15). P. Choffat refers to Cenomanian eruptions in Portugal (*Journ. Sciencias Math. Phys. Natur.*, Lisbon, 1884). A. E. Lagorio has found in the Crimea a series of sheets, dykes and bosses, ranging from nevadites to basalts, which may be of Jurassic age.

that the general order of succession in the appearance of volcanic rocks at each centre of eruption was first Propylite, followed successively by Andesite, Trachyte, Rhyolite and Basalt.[1] This sequence he believed to be seldom or never complete in any one locality—sometimes only one member of the series may be found; but when two or more occur, they follow, in his opinion, this order, basalt being everywhere the latest of the series. Subsequent research, however, has shown that though his generalisation expressed a natural sequence frequently observable, it was not of universal application, and especially failed in the case of eruptions from a volcanic centre where frequent repetitions of whole or partial series may occur.[2] A few examples of the observed order of appearance at different volcanoes may here be cited.

The researches of Bergeat among the Lipari Islands have shown that the earliest eruptions at that centre consisted of felspar-basalts with from 51 to 55 per cent of silica, followed by andesites with gradually increasing acidity until their silica rose to over 61 per cent. These andesites belonged to the most vigorous period of activity. After them came a remarkable change in the geographical distribution as well as in the chemical composition of the lavas emitted. From some vents, as those of Lipari and Vulcano, liparites have been poured out containing sometimes as much as 74·5 per cent of silica, while from other neighbouring orifices basalts and leucite-basanites have been emitted which are more basic even than the basalts at the beginning of the series.[3]

The Eureka district, Nevada, has furnished a large body of important evidence regarding the sequence of volcanic eruptions. As the result of his prolonged observations Mr. Arnold Hague gives the following as the order of appearance of the lavas in that region: (1) Hornblende-andesite; (2) Hornblende-mica-andesite; (3) Dacite; (4) Rhyolite; (5) Pyroxene-andesite; (6) Basalt.[4]

In the volcanic area of the Yellowstone Park, Mr. Iddings found the succession to be andesites of mean composition, including hornblende-andesite and hornblende-mica-andesite, followed by more basic andesite and basalt, and more siliceous andesite and dacite, and by basalt, rhyolite and basalt.[5]

The general result of the observations at regions of still active or extinct volcanoes, while establishing the fact of a gradual change in the character of the magma from which the lavas are derived, suggests that at first when volcanic activity begins the magma is frequently if not always one of intermediate composition, but inclining towards the basic rather than to the acid side; that by degrees a process of differentiation sets in whereby, within the same magma-reservoir, the basic constituents tend towards one quarter while the acid are left or move towards another; that in this way, from different, or even sometimes from the same, funnels of discharge, now acid and now basic lavas are emitted; and that usually the final emissions are of a basic character.

These conclusions have been derived from a study of local volcanic centres, and may require modification in regard to the history of fissure-eruptions. Mr. Iddings has remarked that at a volcanic centre differentia-

[1] "The Natural System of Volcanic Rocks," *Californ. Acad. Sci.* 1868.

[2] J. P. Iddings, *Bull. Phil. Soc. Washington*, xii. (1892), p. 144.

[3] 'Die Aeolischen Inseln,' p. 268.

[4] "Geology of the Eureka District," *Monograph* xx. *U. S. G. S.* (1892), p. 290.

[5] *Bull. Phil. Soc. Washington*, xii. p. 145.

tion will take place independently of other centres within a relatively small body of magma, at frequent intervals or continuously, and with the emission of a comparatively limited amount of lava at any one time, whereas in fissure-eruptions the outbursts may be few, with long pauses between and the discharge of comparatively large volumes of lava at each outburst, and with less variation in the chemical and mineralogical composition of the material discharged.[1] It may be added that in some cases at least the differentiation in areas of fissure-eruptions, when it has advanced so far as to give rise to highly acid compounds, has at the same time become local in its manifestations. Thus along the vast region of Tertiary basalt which stretches in broken tracts from Antrim in Ireland to the north of Iceland, protrusions of granophyre and liparite have broken through the basalt in many places, forming prominent hills or even groups of hills, but never extending far over the basic sheets. But there also the latest eruptions have been of a basic character, for the acid masses are traversed by numerous dykes of basalt.

As the older ejections of a living volcano are usually more or less buried under later materials, the petrographical history of the lavas cannot always be satisfactorily studied there. It is among the volcanoes of former geological periods, where denudation has laid bare the inner architecture of the mountains, that this history can be most completely unravelled. Further consideration of the subject will therefore be postponed to Book IV. Part VII., where the plutonic and volcanic rocks that form part of the earth's crust will be described.

## § 5. Causes of Volcanic Action.

No section of dynamical geology offers greater difficulties for solution than the problems of volcanism, and in none have theory and speculation been more rife. In the early days of the science, Werner and his school got rid of these difficulties by boldly affirming volcanoes to be a modern and insignificant phenomenon, easily explicable on the supposition that subterranean beds of coal have taken fire. Afterwards came the notion of great chemical changes within the earth, such as those which Sir Humphry Davy showed would result from the access of water to bodies of metallic sodium and potassium. When geologists had come to believe without hesitation that the great mass of the earth consists of molten liquid enclosed within a comparatively thin shell, they naturally looked upon volcanic action as one of the obvious and inevitable reactions of an interior so constituted upon its cool external envelope, though they could form no clear or generally acceptable opinion as to the immediately determining cause of a volcanic eruption. The favourite conception was one that invoked the contraction of the earth in consequence of its secular cooling. Thus Cordier calculated that a contraction of only a single millimetre (about $\frac{1}{25}$th of an inch) would suffice to force out to the surface lava enough for 500 eruptions, allowing 1 cubic kilometre (about 1300 million cubic yards) for each eruption.[2]

[1] *Op. cit.* p. 182.

[2] 'Essai sur la Température de l'Intérieur de la Terre,' Paris, 1827.

But something more than mere contraction was needed to account for the fitful outbreaks and singularly variable intensity of volcanic action. The most ingenious and elaborate application of the idea of secular contraction was that worked out by the late Robert Mallet,[1] who maintained that all the present manifestations of hypogene action are due directly to the more rapid contraction of the hotter internal mass of the earth and the consequent crushing in of the outer cooler shell. He pointed to the admitted difficulties in the way of connecting volcanic phenomena with the existence of internal lakes of liquid matter, or of a central ocean of molten rock. Observations made by him, on the effects of the earthquake shocks accompanying the volcanic eruptions of Vesuvius and of Etna, showed that the focus of disturbance could not be more than a few miles deep; that, in relation to the general mass of the globe, it was quite superficial, and could not possibly have lain under a crust of 800 miles or upwards in thickness. The occurrence of volcanoes in lines, and especially along some of the great mountain-chains of the planet, was likewise dwelt upon by him as a fact not satisfactorily explicable on any previous hypothesis of volcanic energy. But he contended that all these difficulties disappear when once the simple idea of cooling and contraction is adequately realised. "The secular cooling of the globe," he remarks, " is always going on, though in a very slowly descending ratio. Contraction is therefore constantly providing a store of energy to be expended in crushing parts of the crust, and through that providing for the volcanic heat. But the crushing itself does not take place with uniformity; it necessarily acts *per saltum* after accumulated pressure has reached the necessary amount at a given point, where some of the pressed mass, unequally pressed as we must assume it, gives way, and is succeeded perhaps by a time of repose, or by the transfer of the crushing action elsewhere to some weaker point. Hence, though the magazine of volcanic energy is being constantly and steadily replenished by secular cooling, the effects are intermittent." He offered an experimental proof of the sufficiency of the store of heat produced by this internal crushing to cause all the phenomena of existing volcanoes.[2] The slight comparative depth of the volcanic foci, their linear arrangement, and their occurrence along lines of dominant elevation become, he contended, intelligible under this hypothesis. For since the crushing in of the crust may occur at any depth, the volcanic sources may vary in depth indefinitely; and as the crushing will take place chiefly along lines of weakness in the crust, it is precisely in such lines that crumpled mountain-ridges and volcanic funnels should appear. Moreover, by this explanation its author sought to harmonise the discordant observations regarding variations in the rate of increase of temperature downward within the earth, which have already been cited and referred to unequal conductivity in the crust (p. 62). He pointed out that in some parts of the crust the crushing must be much greater than in other parts; and since the heat "is directly proportionate to the local tangential pressure which produces the crushing and the resistance thereto," it may vary indefinitely up to actual fusion. So long as the crushed rock remains out of reach of a sufficient access of subterranean water, there would, of course, be no disturbance. But if, through the weaker parts,

[1] *Phil. Trans.* 1873. See also Daubrée's experimental determination of the quantity of heat evolved by the internal crushing of rocks. 'Géologie Expérimentale,' p. 448. For adverse criticisms of Mallet's views see Hilgard, *Amer. Journ. Sci.* vii. (1874); O. Fisher, *Q. J. G. S.* August 1875, *Phil. Mag.* Feb. 1876, and 'Physics of the Earth's Crust,' chap. xxii. Mallet's reply is in *Phil. Mag.* for July 1875.

[2] The elaborate and careful experimental researches of this observer will reward attentive perusal. Mallet estimates from experiment the amount of heat given out by the crushing of different rocks (syenite, granite, sandstone, slate, limestone), and concludes that a cubic mile of the crust taken at the mean density would, if crushed into powder, give out heat enough to melt nearly 3½ cubic miles of similar rock, assuming the melting-point to be 2000° Fahr. (*postea*, p. 400).

water enough should descend and be absorbed by the intensely hot crushed mass, it would be raised to a very high temperature, and, on sufficient diminution of pressure, would flash into steam and produce the commotion of a volcanic eruption.

This ingenious theory requires the operation of sudden and violent movements, or at least that the heat generated by the crushing should be more than can be immediately conducted away through the crust. Were the crushing slow and equable, the heat developed by it might be so tranquilly dissipated that the temperature of the crust would not be sensibly affected in the process, or not to such an extent as to cause any appreciable molecular re-arrangement of the particles of the rocks. But an amount of internal crushing insufficient to generate volcanic action may have been accompanied by such an elevation of temperature as to induce important changes in the structure of rocks, such as are embraced under the term "metamorphic."

By common consent geologists have recognised that the source of volcanic energy must be sought in the high temperature of the interior of the globe. They agree that the main proximate cause of the ordinary phase of eruptivity marked by the copious evolution of steam and the abundant production of dust, slags and cinders from one or more local vents, is obviously the expansive force exerted by vapours dissolved in the molten magma from which lavas proceed. Whether and to what extent these vapours are parts of the aboriginal constitution of the earth's interior, or are derived by descent from the surface, is however a question on which opinions differ. The abundant occlusion of hydrogen in meteorites, the discovery of large volumes of this and other gases within the minute pores of many different kinds of rock (*ante*, p. 142), and the capacity of many terrestrial substances, notably melted metals, to absorb large quantities of gases and vapours without chemical combination, and to emit them on cooling with eruptive phenomena not unlike those of volcanoes, have led some observers to conclude that the gaseous ejections at volcanic vents are essentially portions of the original constitution of the magma of the globe, and that to their escape the activity of volcanic vents is due. Professor Tschermak[1] in particular has advocated this opinion, and it has been adopted by other able observers.[2]

On the other hand, since so large a proportion of the vapour of active volcanoes consists of steam, many geologists have urged that this steam has in great measure been supplied by the descent of water from above ground. The floor of the sea and the beds of rivers and lakes are all leaky. Moreover, during volcanic eruptions and earthquakes, fissures no doubt open under the sea, as they do on land, and allow the oceanic water to find access to the interior.[3] Again, rain sinking beneath the

[1] Professor Tschermak has suggested that if 190 cubic kilometres, of the constitution of cast-iron, be supposed to solidify annually, and to give off 50 times its volume of gases, it would suffice to maintain 20,000 active volcanoes. *Sitz. Akad. Wissen. Wien*, lxxv. (1877), p. 151. A. C. Lane, "Geologic Activity of the Earth's originally absorbed Gases," *Bull. Geol. Soc. Amer.* v. (1894), pp. 259-280.

[2] See, for example, Reyer's 'Beitrag zur Physik der Eruptionen,' Vienna, 1877. Stubel, as the result of his long-continued study of volcanoes, alike in the Old and the New Worlds, has come to the confident conviction that volcanic eruptions do not depend upon any source from outside, but that the magma is itself the cause and source of the energy ("deren Ursache und Trägerin das Magma selbst ist"); 'Vulcanb. Ecuador,' p. 358.

[3] Professor Moseley mentions that during a submarine eruption off Hawaii in 1877 "a

surface of the land percolates down cracks and joints, and infiltrates through the very pores of the rocks. The presence of nitrogen among the gaseous discharges of volcanoes may indicate the decomposition of water containing atmospheric gases. The abundant sublimations of chlorides are such as might probably result from the decomposition of sea-water. To some extent surface-waters doubtless do reach the volcanic magma.

It appears to be probable that, somewhat like the reservoirs in which hot water and steam accumulate under geysers, the subterranean magma receives a constant influx of water from the surface, which cannot escape by other channels, but is absorbed by the internal magma at an enormously high temperature and under vast pressure. In the course of time, the materials filling up a volcanic chimney are unable to withstand the upward expansion of this imprisoned vapour or water-substance, so that, after some premonitory rumblings, the whole opposing mass is blown out, and the vapour escapes in the well-known masses of cloud. Meanwhile, the removal of the overlying column relieves the pressure on the lava underneath, saturated with vapours or superheated water. This lava therefore begins to rise in the funnel until it forces its way through some weak part of the cone, or pours over the top of the crater. After a time, the vapour being expended, the energy of the volcano ceases, and there comes a variable period of repose, until a renewal of the same phenomena brings on another eruption. By such successive paroxysms, the forms of the internal reservoirs and tunnels may be changed; new spaces for the accumulation of superheated water being opened, whence in time fresh volcanic vents issue, while the old ones gradually die out.[1]

An obvious objection to this explanation is the difficulty of conceiving that water should descend at all against the expansive force within. But Daubrée's experiments have shown that, owing to capillarity, water may permeate rocks against a high counter-pressure of steam on the further side, and that so long as the water is supplied, whether by minute fissures or through pores of the rocks, it may, under pressure of its own superincumbent column, make its way into highly heated regions.[2]

fissure opened on the coast of that island, from a few inches to three feet broad, and in some places the water was seen pouring down the opening into the abyss below." 'Notes by a Naturalist on the *Challenger*,' p. 503. It is well known that in the island of Cephalonia the sea has for generations been flowing into the fissured limestone in volume sufficient to be used for working corn-mills. No altogether satisfactory explanation of the phenomenon has been proposed. Messrs. F. W. and W. O. Crosby have suggested that the water descends as in one arm of a syphon, and after reaching a considerable depth and acquiring in consequence a much higher temperature, re-ascends by another arm and finds an outlet under the sea. "The Sea-mills of Cephalonia," *Technological Quarterly*, ix. (1896), p. 6.

[1] The potent part taken by water is well expressed by Prestwich ('Controverted Questions in Geology,' 1885, Art. iv.), who thought, however, that it was only a secondary part, and that the main cause of volcanic action was to be sought in a modification of the old hypothesis of the contraction of the solid crust upon a yielding and hot nucleus.

[2] Daubrée, 'Géologie Expérimentale,' p. 274; Tschermak, as cited above; Reyer, 'Beitrag zur Physik der Eruptionen,' § i. Experience in deep mines rather goes to show that the permeation of water through the pores of rocks gets feebler as we descend.

In his work on the volcanoes of Ecuador, Dr. Stübel, who has devoted a long life to the study of volcanic phenomena, sums up the conclusions to which he has come with regard to the origin and history of the volcanic energy of the globe. Firmly convinced that the source of this energy resides in the molten magma itself, he sets out to show from the volcanoes of Ecuador, Mexico and Syria that the present foci of eruption cannot be deep-seated, but probably lie at no great depth beneath the surface. He conceives them to be entirely enclosed spaces of molten material, and believes that the cause of their eruptive action is to be found in a cooling process, in the course of which a more or less sudden increase of volume plays the most essential part. This result is not brought about through the whole body of the magma, but different portions are successively brought under its influence. He cites numerous observations on the behaviour of melted substances at furnaces, laboratories, and at volcanoes like Kilauea, to show how widespread is this expansion in the process of cooling. He emphasises the important part taken by the gases in the magma, though he does not appear able to understand how they of themselves can give rise to a volcanic eruption. He thinks that as they rise through the magma they cause it to swell upward in the direction of escape to the surface, and allow it to exert an enormous force on its surroundings. He speculates further on the probable history of volcanic phenomena in the geological past. Starting with the globe as a mass of molten material, he pictures the repeated and gigantic outpourings of the magma over the thin crust, whereby the surface became coated with a thick mantle of solidified rock.[1] By this world-wide extravasation and by the augmentation in volume of the constantly thickening crust, an imperceptible increase of the earth's diameter is admitted as a result, with all the cosmical consequences that would necessarily follow therefrom. Eventually, as the crust thickened the contest between its resistance and the expansive force of the material reached a climax. A grand "catastrophe" took place. Vast volumes of molten rock were discharged over the surface far exceeding any discharges before or since; but that episode marked the close of the direct access of the great central magma to the surface. So vast, however, was the volume of material then poured out that peripheral magma-reservoirs were formed in it. These, which have necessarily been driven nearer and nearer to the surface by the continuous cooling of the interior, are regarded as the sources of our present active volcanoes. The author of this singular theory does not deal with the evidence supplied by the widespread plications and overthrusts that the earth's crust has undergone shrinkage rather than expansion. Nor is his explanation of the process of eruption quite intelligible. It is not easy to understand how the cooling and consequent expansion of the magma below Stromboli, for instance, could continue for many centuries to maintain the same constant condition of eruptivity.

For some of the latest views regarding the nature and origin of volcanic action we are indebted to Professor Arrhenius of Stockholm, whose observations on the probable condition of the earth's interior have been already cited (*ante*, p. 72), and who, bringing the results of modern physical and chemical research to a consideration of the subject, confirms what has been the growing belief on the part of geologists in regard to this part of their science. Insisting on the enormous energy of the water-vapour with which, at temperatures far above the critical point, the magma is charged, he compares the process of the ascent and explosive discharge of lava and fragmentary materials in a volcanic vent to the action of a geyser. At a depth of 540 metres the vapour in the magma must press upward through the molten mass in gas bubbles, and as it escapes, the column of liquid is forced upward, sometimes

[1] He terms this process "Panzerung," covering with a coat of mail.

even with explosive violence. At the end of the eruption all the water in the lava column must again be in equilibrium down to that depth, and if no other agency intervened the molten rock would gradually cool and stiffen, so that no further discharge would take place in that funnel. But observation shows that eruptions may continue constant at the same spot for centuries and, as at Stromboli, may be as frequent as those of geysers. This recurrence and persistence would not be possible unless water were constantly supplied to the magma below. This water, not in a fluid but in a gaseous state, finds its way down to the magma and is absorbed by it with great energy. The gaseous water above the critical temperature, in consequence of the enormous pressure (1000 atmospheres at 10,000 metres down) beneath the surface, may have the same density as liquid water, probably rather less, and will press into the magma. We must conceive of the sea-bottom with its joints, fractures and capillaries as a semi-permeable membrane, the pores of which are wide enough to let fluid or gaseous water pass through.

Moreover, as the investigations of recent years have shown, we must grant to the water entirely different properties from those to which we are accustomed above ground. At ordinary temperatures water is a very weak base or acid. At 18° it is about one hundred times weaker than silicic acid, which is the chief acid in the composition of the magma, and it can therefore only to an imperceptible degree abstract the silicic acid from the scarcely soluble silicates. But by increase of temperature the relations of the two bodies are entirely changed. At about 300° it is estimated that water and silicic acid are about equally strong, but that at 1000° water is some eighty times, and at 2000° about three hundred times stronger than that acid. Water coming in contact with a viscous magma at temperatures between 1000° and 2000° will act there as a powerful acid, whereby free silicic acid and bases arise which, by mixture with the unchanged magma, pass into acid and basic silicates, while the addition of water makes the compound more readily fluid and causes it to swell and increase in volume. The magma is thus impelled to rise in the volcanic chimney, and in its ascent is there more rapidly cooled. The water, in consequence of the diminution of temperature, becomes an increasingly weaker acid, and large quantities of it are expelled by the silicic acid from the hydrates; the pressure of the vapour rises in spite of the decrease of temperature, and if the water-charged top of the magma-column comes near enough to the surface, explosions of steam break their way out above ground. It may be conjectured that even an earlier separation of the strongly condensed water may take place, and that by reason of its lower density it rises to the surface and passes with violence into steam. At all events, such a separation of solutions in two different parts with a falling temperature is an ordinary occurrence.

The similarity of the funnel of a volcano to that of a geyser is, according to this view, tolerably close. In both cases it is water that plays the chief part in eruption, though in that of the volcano the water is for the most part in chemical combination. When the pressure of

the water-vapour below overcomes that of the overlying column, an explosion takes place, followed in the volcanic funnel by the clearing out of the crater and throat of the volcano, and by further explosions consequent on the clearance thus effected. This process continues until in the geyser the water has cooled down sufficiently not to be able to supply more water-vapour of the requisite tension, and in the volcanic funnel until so much water is given off from the magma that the pressure of what remains cannot overcome the overlying pressure. After water enough has once more found its way into the magma the operation is renewed.

When a volcanic chimney is wide, the cooling of the magma plays a more extraordinary part in the uprise of the molten mass. No violent explosions then occur; only on the surface of the lava there goes on a kind of quiet simmering or sputtering from the escape of steam. This condition appears in the great outflows from Kilauea and the Icelandic volcanic fissures, where the lava flows out tranquilly in all directions, much as water would do.[1]

While this explanation may not improbably be confirmed by further investigation, and be found to be applicable to most forms of volcanic activity, there is always a possibility that other causes which have not yet been suspected may eventually be discovered to co-operate in the production of the eruptive phenomena of volcanoes. For example, it is not unreasonable to suppose that in some places the ordinary appearances of the milder phases of volcanic action may be simulated by some of the reactions described by M. Moissan as observable in metallic carbides (*ante*, p. 270). He has called attention to the hydrocarbons associated with the peperites of the Limagne in Central France. These rocks appear in many cases to fill actual volcanic vents in which there would be the readiest channels of communication between the internal magma and the surface. The presence of asphaltum and mineral-oil at some of the *puys* of Auvergne was known to Guettard, the original discoverer of the volcanic origin of these cones, who cited it as proof that volcanic action arises from the combustion of bituminous materials within the earth.[2] A recent boring at Riom, quoted by M. Moissan, was sunk to a depth of 1200 metres, and yielded a few litres of petroleum, which he thinks probably came from the action of water upon metallic carbides at some considerable depth.[3] It is conceivable, that after prolonged volcanic activity and the consequent evisceration of a portion of the terrestrial crust a passage may be opened for the descent of water to deeper parts of the magma, where metallic carbides may be massed together, and that in this way liquid and gaseous hydrocarbons may be evolved. The oxidation of these products would give rise to carbonic acid gas, which, as we have seen, is a common sign of the last stages of volcanic action.

[1] S. Arrhenius in the paper already quoted on p. 72, from which this brief digest of his views is taken.

[2] *Acad. Royale des Sciences*, 1756, p. 52.

[3] *Proc. Roy. Soc.* lx. (1897), p. 156.

Some interesting observations made by Professor Issel at Zante afford some support to the suggestion that volcanic phenomena of at least a mild type may be produced in connection with the evolution of hydrocarbons. In the southern part of that Greek island bituminous springs have been known from the time of Herodotus, who describes them. The place has also long been noted for its earthquakes, which have sometimes caused great damage, as happened in the winter and spring of 1893. The effects and causes of these movements were studied by M. Issel in association with M. Agamennone, who published an account of their observations.[1] About the beginning of 1895 the vibrations of the ground after a period of comparative quiet became more violent, and culminated in a violent shock with a detonation like the discharge of cannon and an outrush of yellow flames from the larger of the two bituminous basins. After a few days of repose another tolerably strong shaking took place, and a column of water and bitumen rose out of the adjacent sea, which remained in a much agitated state, while quantities of blackish scoriæ were thrown ashore. From the evidence he could collect, M. Issel believed that the following conclusions might be legitimately drawn. Each of two bituminous springs, one subaerial the other submarine, displayed at a short interval of time a small eruptive paroxysm. This paroxysm presented igneous phenomena, with the projection of aeriform, liquid, viscous and perhaps even solid materials, and was accompanied with a re-awakening of the local seismic activity. According to all appearance, the substances ejected from the submarine orifice included scoriaceous material, which bore evident signs of igneous fusion and resembled certain secondary products of metamorphism.[2]

In concluding this section we may note the interest attaching to any connection that could be demonstrated between volcanic action and the occurrence of movements in the crust of the globe—for example, between some of the great orographic plications and displacements and the outbreak of volcanic activity, either from single volcanoes or from fissure eruptions. Perhaps the most striking instance of an apparent connection between such terrestrial disturbances and eruptive phenomena is that supplied by the great volcanic semicircle that sweeps from Central France by the Eifel, Hochgau and Bohemia into Hungary, and which has been referred to the dislocations consequent on the upheaval of the Alps.[3] It is possible that some similar relation may yet be traced between the vast basalt-plateaux of the north-west of Europe and the marked plications and overthrust which occurred in that region in older Tertiary time. In like manner we may inquire whether the still more widespread lavas of the western United States had any connection with the Tertiary orogenic movements which affected that part of the continent.

## Section ii. Earthquakes.[4]

By the more delicate methods of observation which have been invented in recent years, it has been ascertained that the ground beneath

[1] "Intorno ai fenómeni sismici osservati nell' Isola di Zante durante il 1893," *Ann. Uff. Centr. Meteor. Geodyn.* xv. (1894), part i.

[2] *Atti Soc. Ligust. Sci. Nat. Geogr.* vii. (1896), fasc. i. Compare the accounts of the eruptive action of the salinella of Paternò in Sicily, *Bull. Vulcanism. Ital.* ann. v. (1878).

[3] Suess, 'Antlitz der Erde,' i. p. 358, Plate iii.; Julien, *Annuaire du Club Alpin*, 1879-80, p. 446; Michel-Lévy, *Bull. Soc. Géol. France*, xviii. (1890), pp. 690, 841.

[4] To the discussion of the phenomena of Seismology a voluminous literature has been devoted. The following general works of reference on the subject may be cited:—Mallet, *Brit. Assoc.* 1847, part ii. p. 30; 1850, p. 1; 1851. p. 272; 1852, p. 1; 1858, p. 1;

our feet is apparently everywhere subject to continual slight tremors and to minute pulsations of longer duration. The old expression "terra firma" is not only not strictly true, but in the light of modern research seems singularly inappropriate. Rapid changes of temperature and atmospheric pressure, the fall of a shower of rain, the patter of birds' feet,

1861, p. 201; 'The Great Neapolitan Earthquake of 1857,' 2 vols. 1862; A. Perrey, *Mém. Couronn. Bruxelles*, xviii. (1844), *Comptes rendus*, lii. p. 146; R. Falb, 'Grundzüge einer Theorie der Erdbeben und Vulkanensausbrüche,' Graz, 1871; 'Gedanken und Studien über den Vulkanismus, &c.,' 1874; Pfaff, 'Allgemeine Geologie als exacte Wissenschaft,' Leipzig, 1873, p. 224; Schmidt, 'Studien über Erdbeben,' 2nd edit. 1879; 'Studien über Vulkane und Erdbeben,' 1881; Dieffenbach, *Neues Jahrb.* 1872, p. 155; M. S. di Rossi, 'La Meteorologia Endogena,' 2 vols. 1879 and 1882; J. Milne, 'Earthquakes and other Earth-movements,' *Internat. Sci. Series* (contains a bibliography of the subject), 4th edit. 1898; 'Seismology,' *ibid.* 1898. Special papers will be referred to in subsequent pages. Earthquake Committees have been formed in different countries for the study and record of earthquake phenomena, and some of them have published valuable reports. Among these are the Seismological Committee of the British Association, which has issued an annual report since 1895, besides a series of circulars. The "Erdbeben Commission" of the Academy of Sciences of Vienna had published twenty-one reports up to the end of 1879, and thereafter commenced to issue a new series. Still earlier the Société Helvétique des Sciences Naturelles appointed a Committee for the study of earthquakes, which are of such frequent occurrence in Switzerland. In Japan also the enlightened Government of that country organised an Earthquake Investigation Committee in 1892, the way for which had been prepared by the active and well-organised Seismological Society of Japan. The publications of the various national Committees contain not only records of earthquakes, but many discussions of theoretical questions in seismology, and therefore deserve the attention of the student. As samples of the records of local earthquakes, the following list may suffice:—

*British Isles.*—D. Milne [Home], *Edin. New Phil. Journ.* xxxi.-xxxvi.; Mallet's Report in *Brit. Assoc.* cited above; J. P. O'Reilly, *Trans. Roy. Irish Acad.* xxviii. No. xvii. (1884) and No. xxii. (1886); for the last twelve years Mr. Charles Davison has collected all available information regarding British earthquakes, and has published it in the *Q. J. G. S.*, *Geol. Mag.* and *Nature.*

*Germany.*—'Das Mitteldeutsche Erdbeben vom 6 Marz 1872,' K. von Seebach, Leipzig, 1873; 'Das Erdb. Agram, 9th Nov. 1880'; E. G. Harboe in *Gerland's Beiträge zur Geophysik*, iv. (1900), p. 406; v. (1901), pp. 206-238; G. Gerland, *op. cit.* iv. p. 427; v. (1901), pp. i-xvi; E. Rudolph, *op. cit.* v. pp. 1-169; Fuchs, *Neues Jahrb.* 1865-71; 'Erzgebirg. Vogtland. Erdb.' 1876-84; H. Credner, *Zeitsch. Naturwissen.* lvii. (1884); Erdb. 26th Dec. 1888, *Bericht K. Sachs. Ges. Wissen.* February 1889; July and August 1900, *op. cit.* Nov. 1900; Dr. E. von Rebeur-Paschwitz (*Gerland's Beiträge zur Geophysik*, ii. 1895, pp. 211-536) gives a voluminous discussion of earthquake observations at different observatories in 1892-94.

*Austria.*—Reports of the "Erdbeben Commission" above referred to; also F. E. Suess, "Neulengbach, 28th January 1895," *Jahrb. Geol. Reichsanst.* 1895, p. 77; "Laibach, 14th April 1895," *op. cit.* 1897, pp. 411-614; *Tschermak's Min. Mitth.* 1873 and subsequent years.

*Italy.*—Mercalli, in 'Vulcani e fenomeni vulcanici in Italia,' gives an account of Italian earthquakes from 1450 B.C. to 1881 A.D.; also a description of the great earthquake of 1883 in his 'Isola d'Ischia,' Milan, 1884. The effects of the Ischian earthquake were also described in an official report published by the Ministry of Public Works, Rome 1883. See also the *Bollettino del Vulcanismo Italiano*, begun in 1874; and the *Bollettino della Società Sismologica Italiana.*

*Spain and Portugal.*—F. de Montessus de Ballore, "La Peninsula Ibérica Seismica,"

and still more the tread of larger animals, produce tremors of the ground which, though exceedingly minute, are capable of being made clearly audible by means of the microphone and visible by means of the galvanometer. Some tremors of varying intensity, and apparently of irregular occurrence, may be due to minute movements or displacements in the crust of the earth. Less easily traceable are the slow pulsations of the crust, which in many cases are periodic, and may depend on such causes as the diurnal oscillation of the thermal or barometric conditions of the atmosphere, the rise and fall of the tides, &c. So numerous and well-marked are these tremors and pulsations, that the delicate observations which were set on foot to determine the lunar disturbance of gravity had to be abandoned, for it was found that the minute movements sought for were wholly eclipsed by these earth tremors.[1]

The term Earthquake denotes any natural subterranean concussion, varying from tremors so slight as to be hardly perceptible up to severe shocks, by which houses are levelled, rocks dislocated, landslips precipitated, and many human lives destroyed. The phenomena are analogous to the shock communicated to the ground by explosions of mines or powder-works. They may be most intelligibly considered as wave-like undulations propagated through the solid crust of the earth. The nature of earthquake-motion, however, is somewhat complex. Mallet defined it as "the transit of a wave of elastic compression, or of a succession of these, in parallel or intersecting lines through the solid substance and surface of the disturbed country." Mr. Milne has shown that the disturbance may also be due to the transit of waves of elastic distortion. He points out that at least three kinds of movements may be observed, having different velocities of propagation—an undulatory motion on the surface of the earth, elastic waves travelling from the centre of shock to

*Ann. Soc. Espan. Hist. Nat.* tome iii. (1894); "Études relatives au tremblement de terre du 25 Dec. 1884," Fouqué, &c., *Mém. Acad. Sci. Paris*, tome xxx. (1889), pp. 772; C. Barrois, *Mém. Soc. Sci. Lille*, xiv. (1885).

*Scandinavia.*—For many years past E. Svedmark has chronicled every year the Swedish earthquakes in the volumes of the *Geol. Fören. Stockholm Förhandl.*

*United States.*—The Californian earthquakes have been registered since 1889 in the *Bull. U. S. Geol. Survey.* The earthquakes on the Pacific coast from 1769 to 1897 have been catalogued by E. S. Holden, *Smithson. Misc. Coll.* No. 1087 (1898). Earthquakes of special magnitude, such as that of Charleston in 1886, have been the subject of separate accounts.

*Japan.*—The *Transactions of the Seismological Society of Japan* are a storehouse of information in regard to the seismology of that country. A general index to these volumes and to the *Seismological Journal of Japan* (of which eight volumes have appeared up to 1902) will be found at the end of Mr. Milne's 'Seismology.' References to special memoirs on some Japanese earthquakes will be given in subsequent pages.

[1] A. d'Abbadie, 'Études sur la Verticale,' 1872. Plantamour, *Comptes rend.* June 1878, February 1881; *Archives Sciences Phys. Nat.* Geneva, ii. p. 641; v. p. 97; vii. p. 601; viii. p. 551; x. p. 616; xii. (1884), p. 388. G. H. Darwin, *Brit. Assoc.* 1882, p. 95; in this paper Professor Darwin discusses the amount of disturbance of the vertical near the coasts of continents, caused by the rise and fall of the tide. J. Milne, *Trans. Seism. Soc. Japan*, vi. (1883), p. 1; *Geol. Mag.* 1882, p. 482; *Nature*, xxvi. p. 125; 'Seismology,' pp. 266, 272. The essay by S. Günther, quoted on p. 364. The numerous observations made by Rossi in Italy are summarised by G. Mercalli in his work cited above, p. 332.

various points upon that surface, and instantaneous disturbance or an apparent high velocity due to bodily displacement at the centre or within an "earthquake core" and the transmission of elastic or quasi-elastic vibrations or to a combination of such phenomena.[1]

Besides the waves transmitted through the solid crust, others are also propagated through the air and through the ocean. Earthquakes originating under the sea are believed to be more numerous than those on the land. They illustrate well the three kinds of waves associated with the progress of an earthquake. These are: 1st, The complex earth-waves through the earth's crust; 2nd, a wave propagated through the air, to which the characteristic sounds of rolling waggons, distant thunder, bellowing oxen, &c., are due;[2] 3rd, two sea-waves, one of which travels on the back of the earth-wave and reaches the land with it, producing no sensible effect on shore; the other an enormous low swell, caused by the first sudden blow of the earth-wave, but travelling at a much slower rate, and reaching land often several hours after the earthquake has arrived.

**Range of Earth-movements.**—The popular conception of the extent to which the ground moves to and fro or up and down during an earthquake is a great exaggeration of the truth. As the result of very careful measurement with delicate instruments, there appears to be reason to believe that the range of the horizontal motion or distance between the limits of swing at the time of a small earthquake is usually only the fraction of a millimetre, and seldom exceeds three or four millimetres. When the motion rises to 10 millimetres it is dangerous, while if it exceeds 20 it is certain to be accompanied by the shattering of chimneys and other forms of destruction. In a severe earthquake at Tokyo, Japan, on 20th June 1894, the range of motion indicated by the instruments was as much as 63 millimetres (2½ inches), and in that of 1891 it may have been as much as nine or twelve inches. The vertical motion also appears to be exceedingly small. In the 1894 earthquake just referred to, it amounted only to 10 millimetres or less than half an inch.[3]

**Velocity.**—Experiments have been made to determine the velocity of the earth-wave, and its variation with the nature of the material through which it is propagated. Mallet found that the shock produced by the explosion of gunpowder travelled at the rate per second of 825 feet in sand; 1088 feet in schists, slates, and quartzites; 1306 feet in friable granite; and 1664 feet in solid granite, and that as a rule the velocity increased with the force of the initial impulse. General Abbot, by observing the effects of the explosion of dynamite and gunpowder, found the velocity of transmission of the shock to vary from 1240 to 8800 feet per second, and to be greatest where the shock is most violent.[4]

[1] 'Seismology,' p. 119.

[2] On the nature and origin of earthquake sounds, see C. Davison, *Geol. Mag.* 1892, p. 208; *Phil. Mag.* xlix. (1900), pp. 31-70.

[3] Milne, 'Seismology,' p. 78 *et seq.* An ingenious model in wire has been made by Professor Sekiya to illustrate the highly complex path pursued by a particle on the surface of the ground during an earthquake at Tokio, Japan, on 15th January 1887.

[4] *Amer. Journ. Sci.* xv. (1878). Professor J. Milne, experimenting in Japan, has likewise

Professor Fouqué and M. Michel-Lévy conducted a series of experiments in France by explosions in deep mines, so as to measure the velocity from these depths to the surface. They ascertained that in granite (surface) the speed ranged from 2450 to 3141 metres per second; in coal-measures from underground to the surface, it was from 2000 to 2526; in Permian sandstones less compact, 1190; in Cambrian limestone, 632; and in Fontainebleau sandstone about 300.[1]

Observations of the time at which an earthquake has successively visited the different places on its track have shown similar variations in the rate of movement. Thus in the Calabrian earthquake of 1857 the wave of shock varied from 658 to 989 feet per second, the mean rate being 789 feet. The earthquake at Viège in 1855 was estimated to have travelled northwards towards Strasburg at the rate of 2861 feet per second, and southwards towards Turin at a rate of 1398 feet, or less than half the northern speed. The earthquake of 7th October 1874, in Northern Italy, travelled at rates varying from 273 to 874 feet per second. That of 12th March 1873 showed a velocity per second of 2734 feet between Ragusa and Venice; 4101 feet from Spoleto to Venice; 601 feet from Perugia to Orvieto; 1640 feet from Perugia to Ancona; and 1640 (or 2188) feet from Perugia to Rome. The rate of the Central European earthquake of 1872 was estimated to have been 2433 feet; that of Herzogenrath, 24th June 1877, 1555 feet; that of an earthquake at Travancore, in Southern Hindustan, 656 feet in a second.[2] The most accurate measurements and computations of the velocity of earthquake movements are probably those that have been made in Japan. On 9th and 11th December 1891 the mean velocity was determined to be 2·31 kilometres (about 1½ English mile) per second. In the destructive earthquake of 28th October 1891 the average rate was 2·40 kilometres. The same disturbance was felt in Europe; it appears to have travelled to Shanghai at the rate of 1·61 and to Berlin at that of 2·98 kilometres per second. As the result of prolonged observation, Professor Milne concludes that "different earthquakes, although they may travel across the same country, have very variable velocities, varying between several hundreds and several thousands of feet per second; and that the greater the intensity of the shock, the greater is the velocity."[3]

ascertained that a close relation exists between the initial violence of the shock and the velocity of propagation, and that there is a progressive diminution in speed as the wave of shock travels outward from the centre of disturbance. *Proc. Roy. Soc.* 1881; *Phil. Mag.* 1881; *Phil. Trans.* 1882.

[1] *Mémoires Acad. Sci. Inst. France*, tome xxx. (1889), p. 77.

[2] K. von Seebach, 'Das Mitteldeutsche Erdbeben vom 6 März 1872,' Leipzig, 1873. Höfer, *Sitzb. Akad. Wien*, Dec. 1876. A. von Lasaulx, 'Das Erdbeben von Herzogenrath, 22nd Oct. 1873,' Bonn, 1874; 'Das Erdbeben von Herzogenrath, 24 Juni 1877,' Bonn, 1878. G. C. Laube on Earthquake of 31st January 1883, at Trautenau, *Jahrb. Geol. Reichs.* 1883, p. 331. H. Credner on the Earthquakes of the Erzgebirge and Vogtland from 1878 to 1884. *Zeitsch. für Naturwiss.* vol. lvii. (1884). F. Wähner on Agram Earthquake of 9th Nov. 1880, *Sitz. Akad. Wien*, lxxxviii. (1883), p. 15. Di Rossi, 'Meteorologia Endogena,' i. p. 306. P. Serpieri, *Instituto Lombardo*, 1873.

[3] 'Seismology,' p. 110 *et seq.* 'Earthquakes,' p. 94.

During the last ten years seismological self-registering instruments have been set up at many widely separated stations all over the world, and the time of arrival of earthquake waves is thus accurately recorded. In the computations to ascertain the centre of origin from which these waves have travelled, it is necessary in the meantime to assume that the velocity of their propagation is constant, and the most probable rate has been taken to be 1°·6 per minute or approximately three kilometres (9840 feet) per second.[1] Recent observations, however, have shown the velocity to increase with distance from the centre of origin, and that for great distances it is higher than might be expected for waves of compression through a mass of glass or steel; moreover, at any observing station only one disturbance is recorded and not two, which would be the case if the waves passed round the earth, whence it has been inferred that "the movements due to large earthquakes are partly at least propagated *through* the world"[2] (*postea*, p. 371).

**Duration.**—The number of shocks in an earthquake varies indefinitely, as well as the length of the intervals between them. Sometimes the whole earthquake only lasts a few seconds: thus the city of Caracas, with its fine churches and 10,000 of its inhabitants, was destroyed in about half a minute; Lisbon was overthrown in five minutes. "The average duration of 250 earthquakes of moderate intensity recorded by instruments in Tokyo between 1885 and 1891 was 118 seconds. Seven of these, which were strong, were recorded over periods the average of which was six minutes thirteen seconds."[3] But a succession of shocks of varying intensity may continue for days, weeks, or months. The Calabrian earthquake, which began in February 1783, was continued by repeated shocks for nearly four years until the end of 1786.

**Frequency.**—Different earthquake regions vary greatly in the length of time-intervals between the successive shocks. Some are specially sensitive, being shaken at frequent intervals by earthquakes of varying degrees of intensity. Japan is one of the most signal examples of such sensitiveness. Thus during the years 1885 to 1890 there was a gradually increasing number of shocks, which at last numbered rather more than sixty per annum, leading up to the great catastrophe of 28th October in the latter year. After that disastrous event 1132 shocks were recorded in the first ten days, and in the ensuing two years they numbered no fewer than 3364. Even in a region where no severe earthquake has ever been felt within the times of history, frequent minor shocks may take place. At Comrie, in Perthshire, for instance, which is the most sensitive seismic district in Britain, twelve earthquakes occurred within the month of January 1844.

**Periodicity.**—Attempts have been made with more or less success to connect seismic disturbances with different external influences. One of these, to which importance has been attached by some writers, is that of the moon; but the latest re-examination of earthquake lists has shown that little reliance can be placed on the deductions which have been

[1] "Fifth Report of Seismological Investigations," *Brit. Assoc.* 1900.

[2] Milne, 'Seismology,' p. 113.

[3] *Op. cit.* p. 93.

drawn in favour of lunar effects, seeing that the terrestrial disturbances have been equally frequent during each of the lunar periods.[1] More success has attended the endeavour to trace a relation between earthquakes and the succession of the seasons. An annual maximum and minimum has been observed, earthquakes occurring most frequently in winter, and least frequently in summer.[2] Out of 656 earthquakes chronicled in France up to the year 1845, three-fifths took place in the winter, and two-fifths in the summer months. In Switzerland they have been observed to be about three times more numerous in winter than in summer. The same fact is remarked in the history even of the slight earthquakes in Britain, and the law appears to hold in the southern as well as the northern hemisphere, the maximum number of shocks occurring in the one during the time when the minimum takes place in the other. This annual periodicity is attributed by Dr. Cargill Knott to long-continued stresses over large areas caused by barometric pressures and accumulations of snow.[3] No marked difference has been detected in Japan between the number of earthquakes that take place by day and of those by night, but there appears to be a maximum and minimum during each twenty-four hours, which is best marked during the winter months. The maximum which begins at midnight in January grows later until July, when it reaches midday, while from July to December the time of minimum becomes correspondingly earlier.[4]

**Modifying influence of Geological Structure.**—In its passage through the solid terrestrial crust from the focus of origin, the earth-wave must be liable to continual deflections and delays, from the varying geological structure of the rocks. To this cause, no doubt, must be in large measure ascribed the marked differences in the rate of propagation of the same earthquake in different directions. The wave of disturbance, as it passes from one kind of rock to another, and encounters materials of very different elasticity, or as it meets with joints, dislocations, and curvatures in the same rock, must be liable to manifold changes alike in rate and in direction of movement. Even at the surface, one effect of differences of material may be seen in the apparently capricious demolition of certain quarters of a city, while others are left comparatively scatheless. In such cases, it has often been found that buildings erected on loose inelastic foundations, such as low ground overlying soft sand and clay, are more liable to destruction than those placed upon solid rock, especially where high and hard. In illustration of this statement the accompanying plan (Fig. 71) of Port Royal, Jamaica, was given by

[1] Dr. Knott, however, believes that as the maximum frequency of earthquakes falls near the time of perigee it may be connected with the moon's distance. Mr. Oldham also thinks that a maximum frequency of earthquakes may be observed at the time of passage of the circle of maximum horizontal tide-producing force. *Geol. Mag.* 1901, p. 451.

[2] See the works of Perrey cited on p. 359. Schmidt, 'Studien über Erdbeben,' 2nd edit. (1879).

[3] *Proc. Roy. Soc.* lx. (1897). See S. Günther (*Gerland's Beiträge zur Physik*, ii. (1895), pp. 71-152) for a discussion of the influence of atmospheric pressure on the production of microseismic and other movements of the crust.

[4] Milne, 'Seismology,' p. 217.

De la Beche[1] to show that the portions of the town which did not disappear during the earthquake of 1692 were built upon solid white limestone, while the parts built on sand were shaken to pieces.[2] The same conditions are strikingly exemplified in the city of Tokyo, Japan.

It has been observed that an earthquake shock will pass under a limited area without disturbing it, while the region all around has been affected, as if there were some superficial stratum protected from the earth-wave. Humboldt cited a case where miners were driven up from below ground by earthquake shocks not perceptible at the surface; and on the other hand, an instance where they experienced no sensation of an earthquake which shook the surface with considerable violence.[3] Such

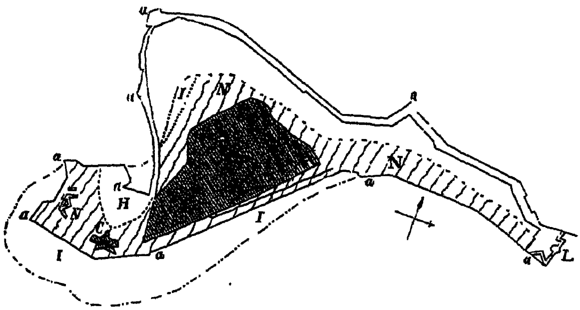


Fig. 71.—Plan of Port Royal, Jamaica, showing the effects of the Earthquake of 1692 (B.)
P C, Portions of the town built on limestone and left standing after the earthquake; a a, L, the boundary of the town prior to the earthquake; N N, ground gained by the drifting of sand up to the end of last century; I L H, additions from the same cause during the first quarter of the present century.

facts bring impressively before the mind the extent to which the course of the earth-wave must be modified by geological structure. In some instances, the shock extends outwards from a common centre, so that a series of concentric circles may be drawn round the focus, each of which will denote a certain approximately uniform intensity of shock ("coseismic lines" of Mallet), this intensity, of course, diminishing with distance from the focus. The Calabrian earthquake of 1857 and that of Central Europe in 1872 may be taken in illustration of this central type. In other cases, however, the earthquake travels chiefly along a certain band or zone (particularly along the flanks of a mountain chain) without advancing far from it laterally. This type of linear earthquake is exemplified by the frequent shocks which traverse Chili, Peru and Ecuador, between the line of the Andes and the Pacific coast.[4]

[1] 'Geological Observer,' p. 246.

[2] The opposite effect has been observed on the island of Ischia, the houses built on loose subsoil generally having suffered much less than the others. There appears, indeed, to be a considerable conflict of testimony on this subject. See Milne, 'Earthquakes,' p. 130.

[3] 'Cosmos,' Art. *Earthquakes*.

[4] For a list of Peruvian earthquakes from A.D. 1570 to 1875, see *Geograph. Mag.* iv. (1877), p. 206. The earthquake of 9th May 1877 at Iquique, and its ocean-wave, are described by E. Geinitz, *Nova Act. Ac. Cæs. Leopold. Car.* xl. (1878), pp. 383-444.

**Extent of country affected.**—The area sensibly shaken by an earthquake varies with the intensity of the shock, from a mere local tract where a slight tremor has been experienced, up to such catastrophes as that of Lisbon in 1755, which, besides convulsing the Portuguese coasts, extended into the north of Africa on the one hand and to Scandinavia on the other, and was even felt as far as the east of North America. Humboldt computed that the area shaken by this great earthquake was four times greater than that of the whole of Europe. The South American earthquakes are remarkable for the great distances to which their effects extend in a linear direction. Thus the strip of country in Peru and Ecuador severely shaken by the earthquake of 1868 had a length of 2000 miles. The great Japanese earthquake of 28th October 1891 shook an area of 243,055 square kilometres, or more than 60 per cent of the whole extent of the empire of Japan, an area equal to the British Isles, Holland and Denmark put together.[1]

But far beyond the regions where the earthquake movement is perceptible by the senses, it is detected and recorded by seismometers. So delicate are these instruments that probably no earthquake of any consequence can now take place without being recorded by them even on the opposite side of the globe. Thus the Assam earthquake of 12th June 1897 was registered by great disturbance of the seismometers at the various observing stations, even as far as Edinburgh, a distance of nearly 8000 kilometres (5000 English miles) from the centre of origin.[2]

**Depth of Source.**—According to Mallet's observations, over the centre of origin the shock is felt as a vertical up-and-down movement (*Seismic vertical*); while, receding from this centre in any direction, it is felt as an undulatory movement, and comes up more and more obliquely. The *angle of emergence*, as he termed it, was obtained by him by taking the mean of observations of the rents and displacements of walls and buildings. In Fig. 72, for example, he concluded that the wall there represented had been rent by an earthquake which emerged to the surface in the path marked by the arrow. The reliance that can be placed on this method is, however, not always very great.[3]

By such observations Mallet estimated the approximate depth of origin of an earthquake. Let Fig. 73, for example, represent a portion of the earth's crust in which at *a* an earthquake arises. The wave of shock will travel outwards in successive spherical shells. At the point *e* it will be felt as a vertical movement, and loose objects, such as paving-stones, may be jerked up into the air, and descend bottom uppermost on their previous sites. At *d*, however, the wave will emerge at a lower angle, and will give rise to an undulation of the ground, and the oscillation of objects projecting above the surface. In rent buildings, the fissures will be on the whole perpendicular to the path of emergence.

[1] B. Kotô, *Journ. Coll. Sci. Japan*, vol. v. part iv. (1893), p. 352. Also a paper by R. D. Oldham, "On the Propagation of Earthquake-motion to Great Distances," *Phil. Trans.* cxciv., A (1900), pp. 135-174.

[2] "Third Report on Seismol. Investig." *Brit. Assoc.* 1898, p. 205.

[3] Milne, 'Seismology,' p. 195.

By a series of observations made at different points, as at $g$ and $f$, a number of angles are obtained, and the point where the various lines cut the vertical ($a$) will mark the area of origin of the shock. By this means, Mallet computed that the depth at which the impulse of the Calabrian earthquake of 1857 was given was about five miles. As the

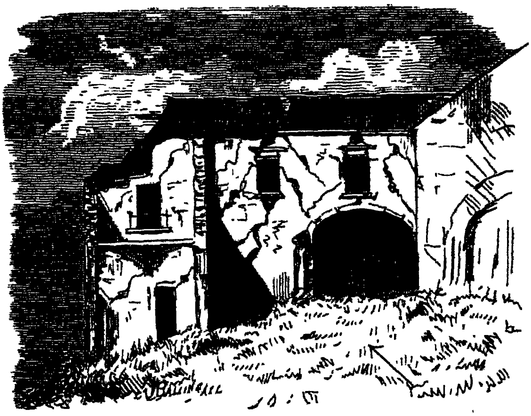

Fig. 72.—Wall shattered by an Earthquake, of which the "path of emergence" has been in the direction shown by the arrow. (After Mallet.)

general result of his inquiries, he concluded that, on the whole, the origin of earthquakes must be sought in comparatively superficial parts of the crust, probably never exceeding a depth of 30 geographical miles. Following another method of calculation, Von Seebach computed that the earthquake which affected Central Europe in 1872 originated at a depth of 9·6 geographical miles; that of Belluno in the same year was estimated by Höfer to have had its source rather more than 4 miles deep;

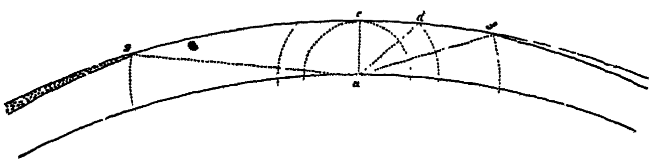

Fig. 73.—Mallet's mode of estimation of depth of source of Earthquake movements.

while that of Herzogenrath in 1873 was placed by Von Lasaulx at a depth of about 14½ miles, and that of 1877 in the same region at about 14 miles.[1]

**Seat of Origin.**—There appears now to be no reason to doubt that the great majority of earthquakes originate under the sea.[2] The submarine tracts more specially liable to them lie along the bases of the

[1] See papers by Höfer and A. von Lasaulx, cited on p. 362. For an account of the various methods employed in estimating the depth of origin of earthquakes, see Milne's 'Earthquakes,' chapters x. and xi. Consult also the *Trans. Seismolog. Soc. Japan.*

[2] The phenomena of submarine earthquakes are discussed by Rudolph in his papers cited *ante*, p. 332.

steep declivities of the continental areas. Such a line of disturbance, for example, lies out at sea along the eastern coast of Japan, where the sea-bottom plunges down into the great abyss of the Tuscarora Deep, the bottom of which lies more than 24,000 feet below the sea-level; and it is from that line that most of the earthquakes, which are so numerous and often so disastrous, arrive in Japan. Thus the seat of the destructive earthquake of 15th June 1896 was situated near the foot of the western slope of that vast depression at a depth of 4000 fathoms, and not at a point but along a line of considerable length. Another similar line of weakness lies along the steep submerged western front of South America between Valparaiso and Iquique, where the bottom likewise sinks into a deep trough.[1] On land the most frequent earthquakes take place along mountain chains, especially those of which the latest upheavals date from late geological time. As many of these mountain chains, particularly when near a coast-line, are dotted with volcanoes, it was formerly believed that earthquakes were especially prominent in volcanic districts. But although they do occur in such areas, they are much more abundant in other non-volcanic regions. The severest European earthquakes, for instance, have taken place not around Etna or Vesuvius, but along the Apennines, the Alps and other districts far removed from any active volcano.

**Distribution.**—While no large space of the earth's surface seems to be free from at least some degree of earthquake-movement, there are regions more especially liable to the visitation. In the Old World, a great belt of earthquake disturbance stretches in an east and west direction, along that tract of remarkable depressions and elevations lying between the Alps and the mountains of Northern Africa, and spreading eastward so as to enclose the basins of the Mediterranean, Black Sea, Caspian and Sea of Aral, and to rise into the great mountain ridges of Central Asia. The borders of the Pacific Ocean are likewise subject to frequent earthquake shocks. Some of the most terrible earthquakes within human experience have been those which have affected the western seaboard of South America. It is worthy of notice that the coasts of the Pacific Ocean more specially liable to convulsions of this nature plunge steeply down into deep water with slopes of one in twenty to one in thirty, while shore-lines such as those of Australia, Scandinavia and the east of South America, where the slope is no more than from one in fifty to one in two hundred and fifty, are hardly ever affected by earthquakes. It should also be remarked that while earthquakes are apt to occur along the flanks of mountain chains and to travel along these lines of elevation, they seldom cross a large chain. In Japan, for example, the earth-waves which arrive from the ocean become feebler as they travel inland, until they are nearly imperceptible in the mountainous backbone of the island, beyond which they rarely extend.[2]

[1] The evidence from chafed and broken telegraph cables as to probable displacements of rock and sediment by submarine seismic disturbances has been collected by Dr. John Milne, "Sub-oceanic Changes," *Geog. Journ.* August and Sept. 1897.

[2] Milne's 'Seismology,' p. 31.

**Causes of Earthquakes.**—Though the phenomena of an earthquake become intelligible as the results of the transmission of waves of shock arising from a centre where some sudden and violent impulse has been given within the terrestrial crust, the origin of this sudden blow can only be more or less plausibly conjectured. Various conceivable causes may, at different times and under different conditions, communicate a shock to the subterranean regions. Such are the falling in of the roof of a subterranean cavity, the explosions of a volcanic orifice, or the sudden snap of deep-seated rocks subjected to prolonged and intense strain. Each of these disturbances no doubt from time to time gives rise to earthquakes.

In countries where the underground rocks are liable to considerable solution by percolating water, and where consequently tunnels and caverns are formed, it is obvious that occasionally the roofs of these empty spaces must collapse, and when this takes place a shock of greater or less intensity will be propagated outward from the centre of disturbance. In the Visp Thal, Canton Wallis, for example, where there are some twenty springs carrying up gypsum in solution (one of them to the extent of 200 cubic metres annually), continued rumblings and sharp shocks are from time to time experienced. In July and August 1855, these movements lasted upwards of a month, and gave rise to the fissuring of buildings and the precipitation of landslips. In the honeycombed limestone tract of the Karst, also, earthquakes of varied intensity are of constant occurrence. Again, the long-continued and copious discharge of materials from a volcanic vent may give rise to one or more large cavernous spaces in the terrestrial crust, which, perhaps long after the close of eruptive activity, may collapse and produce an earthquake. But the shocks originated in these ways are so local and generally so shallow that they can hardly cause any widespread disturbance.

More important are the earthquakes that arise from volcanic explosions. It was formerly, indeed, the general belief that these comprise by far the largest number and the most destructive of all. But, as above stated, this erroneous conception has been disproved by further observation. Not only have earthquakes been found to be more numerous and powerful in non-volcanic than in volcanic regions, but those which accompany even the most violent volcanic explosions have been ascertained to be distinctly more local in their effects than the others. The tremendous catastrophe of Krakatoa in 1883, though it affected the ocean and the air over the whole globe, does not appear to have given rise to any widespread shaking of the terrestrial crust. The great loss of life and property which it caused arose mainly from the inrush of the sea-waves propagated outwards from the site of the volcanic discharge in Sunda Strait. Again, the great explosion of Bandaisan in 1888 shook an area of not more than 2000 square miles. As Mr. Milne has pointed out, it is difficult to imagine that the primary impulse of a shock which will be felt over an extent of five or ten thousand square miles can take its rise at such a mere local focus of energy as that of a volcano.[1] It would seem to be

[1] 'Seismology,' p. 30. Compare P. Rudzki, "Studien aus der Theorie der Erdbeben," *Gerland's Beiträge zur Geophysik*, iii. (1898), pp. 495-540.

necessary that this impulse should be exerted over an area very much larger than can be supposed to belong to even the most powerful volcanic vent.

There is now a general agreement that the cause of the more important earthquakes is to be sought in the effects of terrestrial contraction.[1] Dr. Hoernes, from a study of European earthquake phenomena, came to the conclusion that though some minor earth-tremors may be due to the collapse of underground caverns, and others of local character to volcanic action, the greatest earthquakes are the immediate consequences of the formation of mountains, and he connected the lines followed by earthquakes with the structural lines of mountain-axes. This view has been sustained and extended by the observations of later years. It is now perceived, however, that not merely mountain-chains, but any other part of the earth's crust which is under great strain, may give way suddenly and thus afford the primary impulse of an earthquake. The great lines of plication, whether anticlinal or synclinal, are those where the stresses are severest, and where, therefore, the crust must be most likely from time to time to give way. In the case of geologically ancient mountain-chains the underlying crust has had time to adjust itself to the conditions produced by their uprise; but in the younger chains such stability has not yet been reached, so that under the intense strain of corrugation the rocks occasionally snap along the length of the anticlines or synclines, and thus give rise to the tremors or more violent shocks of mountainous regions like the Alps. Obviously a serious rent in the crust produced in this way, and extending for fifty or a hundred miles, must give rise to a wider disturbance than could be caused by a violent explosion from a single volcanic vent.

The sub-oceanic earthquakes may be traced to the same source of origin. As already stated, they appear to start from the base of the steep submerged slopes of the continents. On the two sides of the Pacific, the land off Japan and off part of the coast of South America rapidly sinks into a deep trough, the bottom of which rises again into the general level of the ocean floor. These troughs may be regarded as deep synclines of the crust, as the mountain-chains are lofty anticlines. In either case the rocks have been bent and thrown into a state of strain from which they obtain relief by occasional fracturing. That some of these submarine operations affect the sea-bottom has now been indicated by the frequent rupture of telegraph cables. Such accidents may no doubt happen from various causes not necessarily seismic; but after these possible causes have been allowed for (and some of them, such as the launching downward of vast quantities of rock-débris, may be due to earthquakes), there seems to be little doubt of the number and potency of the disturbances that arise along the submerged slopes of the continents.[2]

Where the terrestrial crust has been weakened by lines of powerful faults, slips on the downthrow side of such dislocations may from time to

[1] See *postea*, p. 416 *et seq.* Suess, 'Entstehung der Alpen,' Vienna, 1875; Hoernes, "Erdbeben Studien," *Jahrb. Geol. Reichs.* xxviii. (1878), p. 448.

[2] J. Milne, "Sub-oceanic Changes," *Geog. Journ.* x. (1897), pp. 129-146, 259-289.

time take place, and give rise to gentle concussions or more violent earthquakes. Thus the chief earthquake area in the British Isles, that of Comrie, lies on the line of one of the great structural faults of Scotland, the displacement along which has amounted to many thousand feet. The great Japanese earthquake of 1891 was probably caused by a renewal of subsidence along the side of an old fault-line, which resulted in the formation of a fissure along that line, reaching to the surface of the ground and traceable for more than 40 miles. In districts of younger horizontal formations which are not dislocated, earthquakes may nevertheless arise from slipping along lines of dislocation in older formations underneath. Many earthquakes are followed by numerous less violent aftershocks, which probably mark minor ruptures of rock, while the displaced portion of the terrestrial crust is gradually settling down after the main dislocation. Thus after the Japanese earthquake of October 1891, which was manifestly due to fracture and slipping along the line of the fissure, the after-shocks, which, as already stated, numbered 1132 during the first ten days and no fewer than 3364 during the next two years, show how serious was the original displacement, and how gradually the sunken mass accommodated itself to its new position.

If the suggestion above referred to should be eventually established, that the earth-wave is transmitted through the interior of our globe, fresh material will be supplied for discussion of the effective rigidity of the planet. This subject has indeed been already noticed by Professor Arrhenius in the paper on the Physics of Volcanism, from which some quotations have been made in previous pages (*ante*, pp. 72, 355). Reviewing the recent advances in seismology, and especially the evidence as to the rate at which the waves of shock are propagated in the earth from long distances, he remarks that if the earth's interior consisted of solid material, we must assume that the first or preliminary shock propagated in that interior and recorded at a distant seismological station is as violent as or more violent than the principal shock, and that the sole reason for the enormous weakening of the first shock must be because this shock is to an extraordinary degree smothered. This inference points, he thinks, to the very great internal friction within the earth—a property characteristic of fluid and gaseous bodies, especially under high pressure and temperature, in contradistinction to solid bodies. He concludes that earthquake observations afford strong evidence against the solidity of the earth's interior.[1]

**Geological effects.**—These are dependent not only on the strength of the concussion but on the structure of the ground, and on the site of the disturbance, whether underneath land or sea. They include changes superinduced on the surface of the land, on terrestrial and oceanic waters, and on the relative levels of land and sea.

1. Effects upon the soil and general surface of a country.—The earth-wave or wave of shock underneath a country may traverse a wide region and affect it violently at the time, without leaving permanent traces of its passage. The soil may be detached from hill-slopes, carrying

[1] *Op. cit.* p. 409.

with it a wide extent of forest, and leaving in places declivities of bare stone. Blocks of rock, already disengaged from their parent masses on declivities, may be rolled down into the valleys, or where only feebly adherent to the rock *in situ* may be shaken off. Landslips are thus produced, which may give rise to considerable changes of drainage by damming up streams, altering their courses, or giving rise to lakes.[1] In some instances, the surfaces of solid rocks are shattered as if by gunpowder, as was particularly noticed to have taken place among the Primary rocks in the Concepcion earthquake of 1835.[2] It has often been observed also that the soil is rent by fissures which vary in size from mere cracks, like those due to desiccation, up to chasms a mile or more in length and 200 feet or more in depth. Permanent modifications of the landscape may thus be produced. Trees are thrown down, and buried, wholly or in part, in the rents. These superficial effects may, indeed, be soon effaced by the levelling power of the atmosphere. Where, however, the chasms are wide and deep enough to intercept rivulets, or to serve as channels for heavy rain-torrents, they are sometimes further excavated, so as to become gradually enlarged into ravines and valleys, as has happened in the case of rents caused by the earthquakes of 1811-12, in the Mississippi valley. In the earthquake which shook the South Island of New Zealand in 1848, a fissure was formed, averaging 18 inches in width and traceable for a distance of 60 miles parallel to the axis of the adjacent mountain-chain. The subsequent earthquake of 1855, in the same region, gave rise to a fracture which could be traced along the base of a line of cliff for a distance of about 90 miles. Messrs. R. Mallet and T. Oldham have described a remarkable series of fissurings which ran parallel with the river of Calhar, Eastern British India, varying with it to every point of the compass and traceable for 100 miles.[3] The Indian examples have shown the existence of two classes of fissures in earthquakes: first, the important rectilinear rents traceable for long distances, and obviously the superficial manifestation of the underground fault along which the slipping that produces the shock takes place; and second, the mere surface cracks in soil, more rarely in solid rock, due to the passage of the earth-wave, and specially developed parallel to any free surface such as a river-bank towards which the soil can readily move. The first or true fissures or faults may be regarded as parts of the dislocation that cause the earthquake; the second class are mere cracks that arise as a consequence of the movements started by the first.

Another remarkable instance of the first or fault-fissure type was furnished by the great Japanese earthquake of 28th October 1891, which, as above stated, gave rise to a fissure that could be traced along the

[1] Earthquake shocks are believed by Mr. Whitman Cross to have been the initial cause of extensive landslips that have taken place in the Western regions of the United States (*21st Ann. Rep. U. S. G. S.* 1900, part ii. chap. v.). Some of these slides cover areas of several square miles, and may date from Pleistocene time.

[2] Darwin, 'Journal of Researches,' 1845, p. 303.

[3] *Q. J. G. S.* xxviii. p. 257. R. D. Oldham, as cited on next page. For a catalogue of Indian Earthquakes to the end of 1869, see T. Oldham, *Mem. Geol. Surv. India*, xix. part ii.

surface of the country for more than forty miles (Fig. 74). The ground on one side sank from two-thirds of a metre to as much as six metres below that on the other; and not only so, but there was likewise a horizontal displacement, the east side being in places pushed bodily four metres towards the north.[1] In some places the rupture showed itself at the surface in a cracked ridge, like that of a mole when near the surface. The great Indian earthquake of 12th June 1897 gave rise to some important fissures, one of which had in some places rent the solid rock and could be traced for about seven miles.[2]

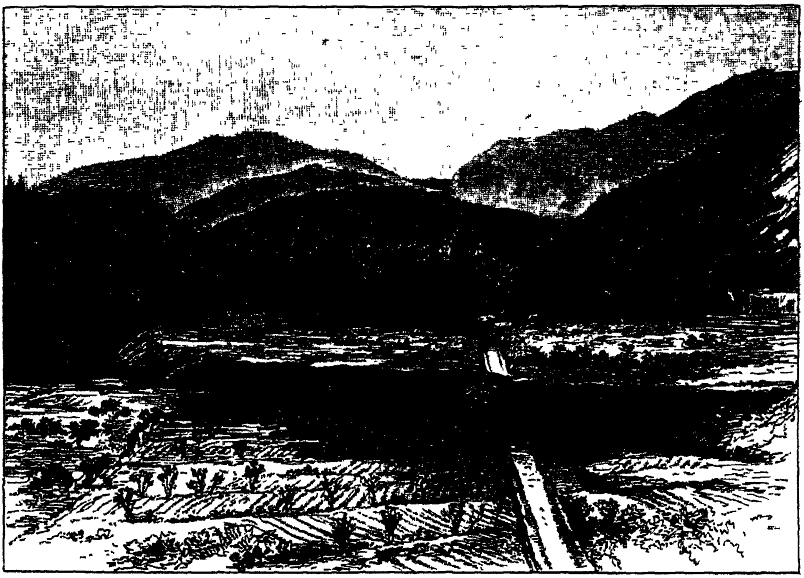

Fig. 74.—Fissure or fault caused by the earthquake of 28th October 1891, in the Neo valley, Japan.

Remarkable circular cavities have been noticed in Calabria, Assam, and elsewhere, formed in the ground during the passage of the earth-wave. In many cases, these holes serve as funnels of escape for an abundant discharge of water, so that when the disturbance ceases they appear as pools. They are believed to be caused by the sudden collapse of subterranean water-channels and the consequent forcible ejection of the water to the surface. Besides water, discharges of various gases and vapours, sometimes combustible, have been noted at the fissures formed during earthquakes.

After the Indian earthquake of June 1897 the rice-fields, which had been carefully levelled to allow them to be flooded to a shallow and uniform depth, were found to be thrown into gentle undulations, with a difference of level of occasionally as much as two or three feet between

[1] B. Kotô, *Journ. Coll. Sci. Japan*, v. part iv. (1893), pp. 329, 339.

[2] R. D. Oldham, "Report on the great Indian Earthquake of 12th June 1897," *Mem. Geol. Surv. India*, xxix. (1899), p. 149.

crest and hollow.[1] A still more remarkable change has been noticed in some earthquakes, where portions of the surface of a country have been compressed so as to bring their several parts nearer to each other. This result was particularly remarked after the central Japanese catastrophe of 1891, above referred to. The horizontal distance between the piers of bridges was shortened, river-beds were contracted from one to two per cent of their former width, and plots of ground were reduced in length in the ratio of ten to seven.

2. Effects upon terrestrial waters.[2]—Springs are affected by earthquake movements, becoming greater or smaller in volume, muddy or discoloured, sometimes increasing in temperature, or even disappearing and finding new exits. Brooks and rivers have been observed to flow with an interrupted course, increasing or diminishing in size, stopping in their flow so as to leave their channels dry, and then rolling forward with increased rapidity. Lakes are still more sensitive. Their waters occasionally rise and fall for several hours, even at a distance of many hundred miles from the centre of disturbance. Thus, on the day of the great Lisbon earthquake, many of the lakes of central and north-western Europe were so affected as to maintain a succession of waves rising to a height of 2 or 3 feet above their usual level. Cases, however, have been observed where, owing to excessive subterranean movement, lakes have been emptied of their contents and their beds have been left permanently dry.

After a severe earthquake new lakes may come into existence. This may arise from at least three causes:—(1) Where the ground has been thrown into undulations and has not recovered its original form, or where it has sunk permanently, the depressions are soon filled with water. Examples of this mode of origin were seen after the earthquake of 1891 in Central Japan. A large tract on the depressed side of the fissure became a lake which had to be drained by a channel cut for the purpose, while two other smaller lakes were also formed in hollows left after the catastrophe.[3] Still more striking were the numerous lakes that arose from interruptions of the drainage-channels by the Indian earthquake of 1897. Mr. Oldham describes a series of sheets of water, one of which was a mile and a half long and 18 feet deep, formed by irregular warping of the ground across the course of a river.[4] (2) Where a line of fissure having a vertical displacement crosses the course of a stream, its fault-scarp will give rise to a waterfall where it faces down stream, and to a lake where it looks the other way. This feature was also well illustrated in the same Indian earthquake. The Chedrang river was crossed a number of times by a fissure which in places had a throw of 25 feet, and after the catastrophe was found to be marked by a succession of lakelets and waterfalls. Not only the main stream was thus affected, but the little tributary rivulets where the fault-scarp rose between them and the river gathered into little pools.[5] (3) One of the most frequent

[1] Oldham, *op. cit.* p. 95.
[2] Kluge, *Neues Jahrb.* 1861, p. 777.
[3] B. Kotô, *op. cit.* p. 335.
[4] 'Indian Earthquake,' p. 152.
[5] *Op. cit.* p. 138.

causes of the ponding up of the drainage of a seismic district is to be found in the fall of masses of rock and earth which, when launched across the course of a stream, dam back the water and give rise to a pool or lake. If this barrier be of sufficient strength, the lake will be permanent; though, from the usually loose, incoherent character of its materials, the dam thrown across the pathway of a stream runs a great risk of being undermined by the percolating water. A sudden giving way of the barrier allows the confined water to rush with great violence down the valley, and to produce perhaps tenfold more havoc there than may have been caused by the original earthquake. When a landslip is of sufficient dimensions to divert a stream from its previous course, the new channel thus taken may become permanent, and a valley may be cut out or widened.

Reference may here be made to an effect of earthquakes on the fauna of terrestrial and oceanic waters, which possesses considerable geological interest. Instances have been observed both on land and sea where the passage of the wave of shock has been highly destructive to some forms of aquatic life. Thus, by the Indian earthquake of 1897, "fishes were killed in myriads as by the explosion of a dynamite cartridge; the fine fishing-pools of the Sumesari river were found devoid of fish, and for days after the earthquake this river was choked with thousands of dead fish floating down from the upper reaches. In the Borpeta subdivision of the Kamrup district the fish were killed in the same manner, and two floating carcases of Gangetic dolphins were seen which had been killed by the shock."[1] In certain ancient geological formations the surfaces of some strata are crowded with the remains of fishes, which are so well-preserved as to show that they must have been suddenly killed and quickly entombed before their bodies had time to decay and the parts to separate. Not improbably such rock-surfaces may sometimes preserve a memorial of old earthquake-shocks.

3. Effects upon the sea.—The great sea-wave propagated outward from the centre of a sub-oceanic earthquake, and reaching the land after the earth-wave has arrived there, gives rise to much destruction along the maritime parts of the disturbed region. When it approaches a low shore, the littoral waters retreat seawards, sucked up, as it were, by the advancing wall of water, which, reaching a height of sometimes 60 feet or more, rushes over the bare beach and sweeps inland, carrying with it everything which it can dislodge and bear away. Loose blocks of rock are thus lifted to a considerable distance from their former position, and left at a higher level. Deposits of sand, gravel, and other superficial accumulations are torn up and swept away, while the surface of the country, as far as the limit reached by the wave, is strewn with débris. If the district has been already shattered by the passage of the earth-wave, the advent of the great sea-wave augments and completes the devastation. The havoc caused by the Lisbon earthquake of 1755, and by that of Peru and Ecuador in 1868, was much aggravated by the co-operation of the oceanic wave. On 15th June 1896, the sea rose along the coast of Nipon, Japan,

[1] R. D. Oldham, *op. cit.* p. 80. See also C. Forbes, *Q. J. G. S.* xiv. (1858), p. 294.

for a distance of 70 miles, and cost the lives of nearly 30,000 of the inhabitants, as it laid whole towns in ruins. The sea-waves on that occasion were propagated across the whole breadth of the Pacific Ocean. They were felt at Honolulu, a distance of 3591 miles, where the sea rose 8 feet above high-water mark, and threw down stone walls. Their mean velocity from Japan to the Hawaiian Islands was 681 feet per second. They were also recorded, though feebler, at Sausalito, in the entrance to San Francisco Bay, a distance of 4787 miles, their mean velocity to that point being 664 feet per second.[1]

The soundings and other explorations connected with the laying and repair of submarine telegraph cables have brought to light the remarkable extent to which the ocean floor is subject to changes of apparently a seismic origin. In some cases vast masses of loose material have been shaken off submarine slopes to lower depths; and quantities of rock-débris have been precipitated to the bottom, burying and often breaking the cables. Changes of depth, sometimes to a hardly credible extent, are likewise reported by those in charge of the cable operations. It is stated that in the Mediterranean great subsidences of the bottom have been observed after earthquakes. "After the Filiatra shock in 1886, it was found, while searching for a broken cable 30 miles off shore, that a depth of 900 fathoms existed where previously there had been only 700 fathoms, and that some four knots of the cable were covered by the 'landslip.'" On the coast of Ecuador, where also the telegraph cables have frequently been broken, the depths are said to have increased from 100 to nearly 200 fathoms.[2]

4. Permanent changes of level.—It has been observed, after the passage of an earthquake, that the level of the disturbed country has sometimes been changed. Thus after the terrible earthquake of 19th November 1822, the coast of Chili, for a long distance, was said to have risen from 3 to 4 feet, so that, along-shore, littoral shells were exposed still adhering to the rocks, amid multitudes of dead fish. The same coast-line has been further upraised by subsequent earthquake shocks.[3] On the other hand, many instances have been observed where the effect of an earthquake has been to depress permanently the disturbed ground. For example, by the Bengal earthquake of 1762, an area of 60 square miles on the coast near Chittagong, suddenly went down beneath the sea, leaving only the tops of the higher eminences above water. The succession of earthquakes which in the years 1811 and 1812 devasted the basin

[1] Davison, *Phil. Mag.* l. (1900), p. 581. On the sea-waves connected with this Japanese earthquake, see J. Milne, *Geograph. Jour.* viii. (1896), p. 157; *Brit. Assoc. Rep.* 1897, p. 25.

[2] Milne, 'Seismology,' p. 35, and "Sub-oceanic Changes," cited *ante*, p. 370. It is difficult to believe that without some stupendous disturbance of the water any part of the Mediterranean floor could have recently suddenly sunk down as much as 200 fathoms, or that the bottom off the coast of Ecuador has lately subsided nearly 600 feet. More probably there has been in some cases a slipping of rock down a submarine face, whereby, without any great horizontal displacement, a line of cable may have been carried down into deeper water.

[3] This elevation is fully described by Lyell in his 'Principles,' but it is discredited by Suess in his 'Antlitz der Erde.' See *postea*, p. 386.

of the Mississippi, gave rise to widespread depressions of the ground, over some of which, above alluded to, the river spread so as to form new lakes, with the tops of the trees still standing above the surface of the water.

## Section iii. Secular Upheaval and Subsidence.

Besides scarcely perceptible tremors and more or less violent movements due to earthquake-shocks, the crust of the earth is generally believed to undergo in many places oscillations of an extremely quiet and uniform character, sometimes in an upward, sometimes in a downward direction. This belief dates back to the early part of the eighteenth century, when Celsius, from numerous observations made by him on the shores of the Baltic, inferred that the land was emerging, by the sinking of the sea, at the rate of 40 inches in a century. His statements were controverted in his own time, though afterwards supported by Linnæus. But it was not until the beginning of the following century that the conviction obtained generally among geologists, when Leopold von Buch, after a full examination of the ground, announced his opinion that Scandinavia was slowly rising out of the sea. From that time the doctrine of secular elevation and depression of land became one of the orthodox parts of the dominant school in geology. It was admitted that these changes of level might be so tranquil as to produce from day to day no appreciable alteration in the aspect of the ground affected, so that perhaps only after the lapse of several generations, and by means of careful measurements, could they really be proved. It was acknowledged that in the interior of a country nothing but a series of accurate levellings from some unmoved datum-line might detect the change of level, unless the effects of the terrestrial disturbance showed themselves in altering the drainage, and that only along the sea-coast was a ready measure afforded of any such movements.

It is customary in popular language to speak of the sea rising or falling relatively to the land. We cannot conceive of any possible augmentation of the oceanic waters, nor of any diminution, save what may be due to the extremely slow processes of abstraction by the hydration of minerals and absorption into the earth's interior. Any changes, therefore, in the relative levels of sea and land must be due to some re-adjustment in the form either of the solid globe or of its watery envelope or of both. Playfair argued at the beginning of last century that no subsidence of the sea-level could be local, but must extend over the globe.[1] But it is now recognised that what is called the sea-level cannot possess the uniformity formerly attributed to it; that on the contrary it must be liable to local distortion from the attractive influence of the land. Not only so, but the level of the surface of large inland sheets of water must be affected by the surrounding high lands.

Mr. R. S. Woodward, whose memoir on this subject has been cited, calculated that in a lake 140 miles broad and 1000 feet deep in the

[1] 'Illustrations of the Huttonian Theory,' 1802. The same conclusion was announced by L. von Buch, 'Reise durch Norwegen und Lapland,' 1810.

middle, the difference of level of the water-surface at the centre and at the margin may amount to between three and four feet.[1] As already stated, he further computed that the effects of the continents of Europe and Asia at the centre in disturbing the sea-level must amount to about 2900 feet, if we suppose that there is no deficiency of density underneath the continent, and to only about 10 feet if we suppose that the very existence of the continent implies such a deficiency.[2]

Various suggestions have been made regarding possible causes of alteration of the sea-level.[3] (1) Subsidence of the floor of the oceanic basins must lower the level of the sea. The elevation of masses of land diminishes the oceanic areas and lowers the sea-level, while the sinking of land produces an opposite effect. Changes in relative areas of land and sea in the past must thus have affected the level of the oceans. (2) A shifting of the present distribution of density within the nucleus of the planet would affect the position and level of the oceans (*ante*, p. 28). (3) As permanent snow and ice represent so much removed from the general body of water on the globe, any large increase or diminution in the extent and thickness of the polar ice-caps must cause a corresponding variation in the sea-level (*ante*, p. 26). (4) A change in the earth's centre of gravity, such as might result from the accumulation of large masses of snow and ice as an ice-cap at one of the poles, has been already referred to (p. 28) as tending to raise the level of the ocean in the hemisphere so affected, and to diminish it in a corresponding measure elsewhere. The return of the ice into the state of water would produce an opposite effect. The attractive influence of the ice-sheets of the Glacial period upon the sea-level over the northern hemisphere has been discussed by various mathematicians, especially by Croll, Pratt, Heath, and Lord Kelvin. Considerable differences appear in their results, according to the conditions which they postulate, but they agree that a decided elevation of the sea-level must be attributed to the accumulation of thick masses of snow and ice. The rise of the sea-level along the border of an ice-cap of 38° angular radius and 10,000 feet thick in the centre is estimated at from 139 to 573 feet.[4] (5) A still further

[1] *Bull. U. S. G. S.* No. 48 (1888), p. 59 ; and *ante*, p. 43.

[2] *Op. cit.* p. 85. See Stokes, *Trans. Camb. Phil. Soc.* viii. (1849), p. 672 ; *Sci. Proc. Roy. Dublin Soc.* v. (1887), p. 652.

[3] Shaler, "Evidences as to Changes of Sea-level," *Bull. Geol. Soc. Amer.* vi. (1895), pp. 141-166.

[4] See Croll, "Climate and Time," chaps. xxiii. xxiv. *Geol. Mag.* 1874. Pratt, 'Figure of the Earth.' D. D. Heath, *Phil. Mag.* xxxi. (1866), pp. 201, 323 ; xxxii. (1866), p. 34. Thomson (Lord Kelvin), *op. cit.* xxxi. p. 305. A. Penck, *Jahrb. Geograph. Gesel.*, Munich, vii. De Lapparent, *B. S. G. F.* xiv. (1886), p. 368 ; *Revue générale des Sciences*, May 1890. R. S. Woodward, *B. U. S. G. S.* No. 48. Von Drygalski, 'Bewegungen der Kontinente zur Eiszeit,' Berlin, 1889. Dr. H. Hergesell (*Gerland's Beiträge zur Geophysik*, i. (1875), pp. 59-114) opposes the view that former shore-lines can be explained by reference to the ice-sheet. Professor Suess believes that the limits of the dry land depend upon certain large indeterminate oscillations of the statical figure of the oceanic envelope ; that not only are "raised beaches" to be thus explained, but that there are absolutely no vertical movements of the crust save such as may form part of the plication arising from secular contraction ; and that the

conceivable source of geographical disturbance is to be found in the fact that, as a consequence of the diminution of centrifugal force owing to the retardation of the earth's rotation caused by the tidal wave, the sea-level must have a tendency to subside at the equator and rise at the poles.[1] A larger amount of land, however, need not ultimately be laid bare at the equator, for the change of level resulting from this cause would be so slow that, as Croll pointed out, the general degradation of the surface of the land might keep pace with it, and diminish the terrestrial area as much as the retreat of the ocean tended to increase it. The same writer further suggested that the waste of the equatorial land, and the deposition of the detritus in higher latitudes, might still further counteract the effects of retardation and the consequent change of ocean-level. (6) Some geologists have contended that where the earth's crust is loaded with thick deposits of sediment or massive ice-sheets it will tend to sink, while on the other hand denudation by unloading it promotes upheaval.

The balance of evidence at present available seems to me adverse to any theory which would account for at least modern changes in the relative level of sea and land by variations in the figure of the oceanic envelope, save to a limited extent by such influences as widespread subsidence of the ocean floor, the attraction caused by extensive masses of upraised land, and possibly in northern and southern latitudes by the attractive influence of large accumulations of snow and ice. These changes of level are rather to be regarded as due to movements of the solid crust. The proofs of upheaval and subsidence, though sometimes obtainable from wide areas, are marked by a want of uniformity and a local and variable character, indicative of an action local and variable in its operations, such as the folding or deformation of the terrestrial crust, and not regular and widespread, such as might be predicated of any alteration of sea-level. While admitting therefore that oscillations of the relative level of sea and land have arisen from some of the causes above enumerated, we may hold that, on the whole and on the great scale, it is the land which is at present rising or sinking, rather than the sea.[2]

This conclusion is supported by the results of the most recent observations and measurements which have been made in different parts of the world, and of some of which a

doctrine of secular fluctuations in the level of the continents is merely a remnant of the old "Erhebungstheorie," destined to speedy extinction. 'Antlitz der Erde,' 1883. He re-states the same views in the French edition of his work published in 1897, with the title of 'Face de la Terre.' Pfaff defended the general opinion against these views in *Z. D. G. G.* 1884.

[1] Croll, *Phil. Mag.* 1868, p. 382. Thomson (Lord Kelvin), *Trans. Geol. Soc. Glasgow*, iii. p. 223.

[2] For the arguments against the view above adopted and in favour of the doctrine that the increase of the land above sea-level is due to the retirement of the sea, see H. Trautschold, *Bulletin Société Imp. des Naturalistes de Moscou*, xlii. (1869), part i. p. 1; 1883, No. 2, p. 341; *B. S. G. F.* (3), viii. (1879), p. 134; but more especially Suess, in his great work above referred to. An excellent summary of the discussion will be found in A. Penck's 'Morphologie der Erdoberfläche,' i. pp. 419-471, and ii. pp. 525-546; see also A. Supan, 'Grundzüge der Physischen Erdkunde,' pp. 278-298; A. Philippson, "Die Bewegungen der Erdrinde in der Gegenwart," *Geograph. Zeitsch.* Hettner, 1895, p. 204; and the literature connected with the emergence of land in Scandinavia and Finland cited on p. 385.

brief notice may here be given. Leaving out of account for the moment the testimony of raised beaches and other evidences of geologically recent changes of level, we may consider those cases where the emergence or subsidence of land has been actually witnessed by man and can be measured. And first in this review comes the classical district of the Gulf of Bothnia, where some of Celsius' original observations were made. It has now been definitely ascertained that the land on both sides of the southern part of that great inlet is emerging from the sea. Those who deny that the movement has been in the land account for the relative change of level by climatal or meteorological oscillations of the water-level. But the evidence for this view, though plausibly urged, is not satisfactory. The Scandinavian and Finnish geologists in particular, who have had the best opportunities of observing the phenomena, have come to the conclusion that they cannot be accounted for by any movement on the part of the waters of the Gulf, that they are markedly local in their distribution, not extending to the south side of the Baltic but well marked on both sides of southern Sweden, and that they point unequivocally to a deformation of the lithosphere. It would appear that the movement has gradually decreased since the time of Celsius. A careful collection of all the known data has been made by L. Holmström,[1] from which we learn that, at Södra Helsö, on the west side of Sweden, fronting the open Skager Rak, there has been an uprise in the fifty years between 1820 and 1870 of 30 centimetres, which is at the rate of 60 centimetres or nearly two feet in a century. On the east coast the rate has varied considerably. At Stockholm between 1774 and 1875 it amounted to 48 centimetres, or at a rate of 0·47 centimetre per annum. Farther north at Barsviken the rate amounts to 1 centimetre a year, while in the Isle of Öland and in southern Sweden the rate falls to a minimum only half that of Stockholm. The facts as observed point to a geanticline, now in progress of formation, and a study of the old strand-lines shows that this uplift has been in progress for a long time, and has upraised the axis of the peninsula to a height of more than 1000 feet. Again, on the coast of Siberia, for 600 miles to the east of the river Lena, and round the islands of Spitzbergen and Novaja Zemlja, the sea appears to stand now at a lower level with regard to the land than it formerly did, and the uprise of the land still continues.

The belief that alterations now taking place in the relative levels of sea and land are to be traced to deformation of the lithosphere rather than to any variation of the surface of the hydrosphere has received strong confirmation from observations made on the coast of Japan. The eastern and southern sides of that country are now undergoing a sensible elevation, which shows itself in the shallowing of harbours, the uprise of rocks to the surface of the sea or above it which were formerly always submerged, the augmentation of the breadth of beach laid bare at low water, the increasing distance from shore to which fishermen have to go to find water of a certain depth, the retreat of the sea to a distance of 180 feet from posts to which ships used to be fastened, the uprise of sea-cliffs full of shell-borings now high above tide-level, and the occurrence of sea-worn caves and hollows and lines of raised beaches. The uplift does not appear to be uniform, and is partly obscured by the sediment carried into the sea by the Sumida and other rivers. Its rate also probably varies. Mr. Milne, who is personally familiar with the evidence, affirms that "at the lowest estimate the observations would indicate that at many places on the coast of Japan land has been emerging from the waters at the rate of about 1 inch per year."[2]

On the other hand, upon the western side of the country there is evidence of a

[1] *K. Svensk. Vet. Akad. Handl.* xxii. (1888), No. 9. See also R. Sieger's paper quoted on p. 385. In Norway there appears to have been, on the whole, no appreciable change of level along the coast for a thousand, perhaps two thousand years. Dr. A. M. Hansen, *Norges Geol. Undersög.* No. 28, Aarbog for 1896-99. But see Reusch, as cited on p. 387.

[2] 'Seismology,' p. 5; see also R. Pumpelly, *Smithson. Contrib. Knowledge*, xv. (1866), p. 108; A. Bickmore, *Amer. Journ. Sci.* xlv. (1868), p. 217.

downward movement now taking place. Grass- and rice-fields are replaced by beaches of sand or shingle; the depth of the sea has increased at rates varying from 1 foot in 16 years to 1 foot in 5 years; rocks have sunk in the water, the height of the tide has increased, buildings are nearer the water than when erected, and the sea is advancing so rapidly that the inhabitants are contemplating removal inland. Some of these changes may be no more than the result of marine erosion; but the general body of evidence "points to the conclusion that certain districts, especially those to the north of Noto, bordering the China Sea, are slowly sinking."[1]

In this region and at the present time there can be no question of any alteration of the general level of the sea. The varying rate of emergence on the east side of the chain of islands and the progress of submergence on the west side point to some unequal movement or warping of the country itself, due to a re-adjustment of the solid crust of the earth.

On the east coast of North America a similar emergence is now taking place along the coasts of Newfoundland and Labrador. There also sunken rocks during the last 30 or more years have come nearer to the surface of the sea, new channels have had to be sought among the shoals for the passage of the fishing-boats, and the stages erected on the shore rocks have had to be lengthened again and again in order to float the small craft. The rate of emergence has not yet been measured, but it is said to be twice as rapid in Northern Labrador as in Newfoundland.[2]

Among the West Indian Islands, which, as will be pointed out further on, furnish widespread proof of recent upheaval, there is likewise evidence of local and limited depression and even of oscillation of level. The Bermudas underwent an uplift by which a marine limestone was raised above the present sea-level to a total height of perhaps 40 or 50 feet. Since that time the ground has been sinking, and the æolian deposits are now partly submerged and are attacked by the waves. At the Bahamas the amount of subsidence is estimated by Agassiz to be perhaps as much as 300 feet.[3]

§ 1. **Upheaval.**—In searching for proofs of movements of upheaval the student must be on his guard against being deceived by any apparent retreat of the sea, which may be due merely to the deposit of gravel, sand, or mud along the shore, and the consequent gain of land. Local accumulations of gravel, or "storm beaches," are often thrown up by storms, even above the level of ordinary high-tide mark. In estuaries, also, considerable tracts of low ground are gradually raised above the tide-level by the slow deposit of mud and growth of vegetation. The following proofs of actual rise of the land are chiefly relied on by geologists.[4]

Evidence from dead organisms.—Rocks covered with barnacles or other littoral adherent animals, or pierced by lithodomous shells, afford presumptive proof of the presence of the sea. A single stone with these creatures on its surface would not be satisfactory evidence, for it might have been cast up by a storm; but a line of large boulders, which had evidently not been moved since the cirripedes and mollusks lived upon them, and still more a solid cliff with these marks of littoral or sub-littoral life upon its base, now raised above high-water mark, would be sufficient to demonstrate a change of level. The amount of this change might be pretty accurately determined by measuring the vertical distance between the upper edge of the barnacle zone upon the

[1] *Op. cit.* p. 3.

[2] R. A. Daly, *Bull. Mus. Comp. Zool. Harvard*, xxxviii. (1902), p. 261.

[3] *Bull. Mus. Comp. Zool.* xxvi.; xxviii. p. 51: Rice, *Bull. U. S. Nat. Mus.* i. No. 25 (1884); R. S. Tarr, *Amer. Geol.* xix. (1897), p. 293.

[4] See "Earthquakes and Volcanoes" (A. G.), Chambers's *Miscellany of Tracts.*

upraised rock, and the limit of the same zone on the present shore. By this kind of evidence, the recent uprise of the coasts of Scandinavia, Japan and other regions, has been proved. The shell-borings on the pillars of the temple of Jupiter Serapis in the Bay of Naples indicate first a depression and then an elevation of the ground to the extent of more than 20 feet.[1] Raised coral-reefs, formed by living species of corals, are found on the coasts of the Red Sea, where they give evidence of having grown up during a time of uplift.[2] Similar reefs are a conspicuous feature of the geology of the West Indian region.[3] One of them has been upraised from 2 to 8 feet above sea-level all along the line of the Florida "Keys." Successive stages in the upheaval are marked among the islands by lines of terraces. Those of Barbadoes, which are particularly striking, consist of successive reefs of coral, rising to a height of about 1100 feet above the sea. In Jamaica three well-marked terraces of upraised coral reefs occur at heights of 10, 25 and 70 feet. In Cuba, a raised coral-reef occurs at a height of 1000 or 1100 feet above the sea.[4] In Peru, modern coral-limestone has been found 2900 or 3000 feet above sea-level.[5] In parts of the Hawaiian Islands the coral reefs have been uplifted about 20 to 25 feet.[6] In the Solomon Islands, evidence of recent uprise is furnished by coral reefs lying at a height of 1100 feet;[7] similar evidence occurs among the New Hebrides at 1500 feet, while elevated coral-reefs and upraised coralliferous limestones abound in the Fiji Islands, and in other archipelagos scattered over the vast basin of the Pacific Ocean.[8] Among the southern islands of Japan elevated coral-reefs occur at many successive heights from 10 to 684 feet above the sea.[9]

The elevation of the sea-bottom can in like manner be proved by dead organisms fixed in their position of growth beneath high-water mark. Thus dead specimens of *Mya truncata* occur on some parts of the coast of the Firth of Forth in considerable numbers, still placed with their siphuncular end uppermost in the stiff clay in which they burrowed. The position of these shells is about high-water mark; but as their existing descendants do not live above low-water mark, we may infer that the coast has been raised by at least the difference between high- and low-water mark, or 18 feet.[10] Dead shells of the large *Pholas dactylus* occur in a similar position near high-water mark on the Ayrshire coast. Even below low-water, examples have been noted, as in the interesting case observed by Sars on the Dröbaksbank in the Christiania Fjord, where dead stems of *Oculina prolifera* (L.) occur at depths of only ten or fifteen fathoms. This coral is really a deep-sea form, living on the western and northern coasts of Norway, at depths of one hundred and fifty to three hundred fathoms in cold water. It must have been killed as the elevation of the area brought it up into upper and warmer

[1] Babbage, *Edin. Phil. Journ.* xi. (1824), p. 91. J. D. Forbes, *Edin. Journ. Sci.* i. (1829), p. 260. Lyell, 'Principles,' ii. p. 164.

[2] W. F. Hume, *Congrès Géol. Internat. Paris* (1900), p. 923.

[3] On changes of level in this region, see A. Agassiz, 'Three Cruises of the *Blake*,' 2 vols. 1888; "A Reconnaissance of the Bahamas and the Elevated Reefs of Cuba," *Bull. Mus. Comp. Zool. Harvard*, xxvi. (1894); "A Visit to the Bermudas in March 1894," *op. cit.* p. 205; "The Florida Elevated Reef," *op. cit.* xxviii. (1896); R. T. Hill, "The Geology and Physical Geography of Jamaica," *op. cit.* xxxiv. (1899); J. W. Spencer, a series of papers on West Indian Islands in *Q. J. G. S.* lvii. (1901), pp. 490-543.

[4] A. Agassiz, *Amer. Acad.* xi. (1882), p. 119.

[5] A. Agassiz, *Bull. Mus. Comp. Zool.* vol. iii.

[6] W. T. Brigham, *Mem. Boston Soc. Nat. Hist.* i. (1868), p. 344; A. Agassiz, *Bull. Mus. Comp. Zool.* xvii. (1889), p. 154.

[7] H. B. Guppy, *Nature*, 3rd January 1884.

[8] A. Agassiz 'The Islands and Coral-reefs of Fiji," *Bull Mus. Comp. Zool.* xxxiii. (1899).

[9] S. Yoshiwara, "Raised Coral-reefs of the Riukiu Curve," *Journ. Coll. Sci. Japan*, xvi. part i. (1901), p. 11.

[10] Hugh Miller's 'Edinburgh and its Neighbourhood,' p. 110.

layers of water.[1] It has even been said that the pines on the edges of the Norwegian snow-fields are dying in consequence of the secular elevation of the land bringing them up into colder zones of the atmosphere.

Any stratum of rock, on the surface of the land, containing marine organisms which have manifestly lived and died where their remains now lie, may be held to prove a change of level between sea and land. In this way it can be shown that most of the solid land now visible to us has once been under the sea. High on the flanks of mountain-chains (as in the Alps and Himalayas), undoubted marine shells occur in the solid rocks.

Fig. 75.—View of a line of ancient Sea-cliff pierced at the base with sea-worn Caves and fronted by a Raised Beach.

Sea-worn Caves.—A line of sea-worn caves, now standing at a distance above high-water mark beyond the reach of the sea, affords evidence of recent change of level. In the accompanying diagram (Fig. 75) examples of such caves are seen at the base of the cliff, once the sea-margin, now separated from the tide by a platform of meadow-land.

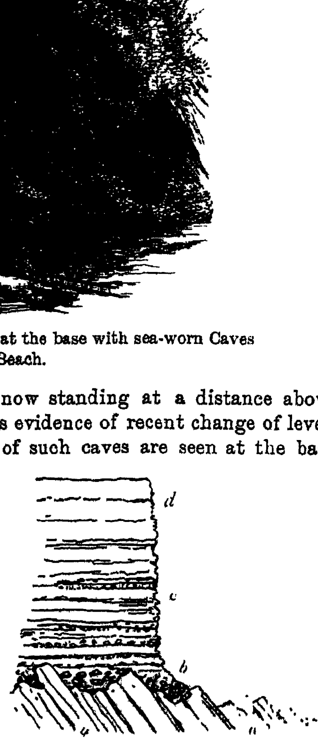


Fig. 76.—Section of a Raised Beach composed of gravel and sand (*b c*) resting on upturned slates (*a*), and passing up into blown sand (*d*) compacted by the decay of abundant land-shells. Fistrall Bay, Cornwall (*B.*).

Raised Beaches or Strand-lines furnish one of the most striking proofs of change of level. A beach or space between tide-marks, where the sea is constantly cutting into the land, grinding down sand and gravel, mingling with them the remains of shells and other organisms, sometimes piling the deposits up, sometimes sweeping them away out into the opener water, forms a familiar terrace or platform on coast-lines skirting tidal seas. According to the character of the land surface and the set of the tides and waves, this platform may be a nearly bare surface of rock which has been levelled by the sea between high- and low-water mark, or it may be formed of littoral accumulations left upon such an underlying surface of erosion. The same strand-line in one part of its course, along an exposed promontory, may be a rock-terrace ("seter" of Norway), and in more sheltered reaches may consist of beach-

[1] Quoted by Vom Rath in a paper entitled "Aus Norwegen," *Neues Jahrb.* 1869, p. 422. For another example, see Gwyn Jeffreys, *Brit. Assoc.* 1867, p. 431.

deposits. When such a terrace, whether of erosion or of deposition, or of both, has emerged well above the reach of the sea, it forms a prominent feature along a coast-line (Figs. 75, 76, 77, 78). The former high-water mark then lies at the inner margin of the platform, above which the old sea-cliff may rise in picturesque crags wherein

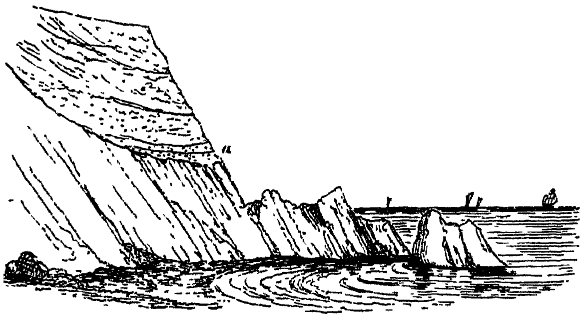


Fig. 77.—View of Raised Beach, Nelly's Cave, Cornwall (*B.*).

the sea-worn clefts and caves are festooned with vegetation. The beach across which the tides once flowed thus furnishes a platform on which meadows, fields, gardens, roads, houses, villages and towns spring up, while a new beach is made below the margin of the uplifted one.

Fig. 78.—View of Terraces, Alten Fjord, Norway.

A series of raised beaches may occur at various heights above the sea. Each terrace marks a former lower level of the land with regard to the sea, and probably a lengthened stay of the land at that level, while the intervals between them represent the vertical amount of each variation in the relative levels of sea and land, and indicate that the interval between the changes was probably too brief for the formation of terraces. A succession of raised beaches, rising above the present sea-level, may therefore be regarded as pointing to a former intermittent upheaval of the country, interrupted by pauses, during which the general level did not materially change. On the hypothesis that they are due to subsidence of the sea-level, it would be necessary to believe that the cause of this subsidence, whatever it might be, acted spasmodically, the intervals of quietude being longer than those of activity.

Raised beaches abound in the higher latitudes of the northern and southern hemispheres, and this distribution has been claimed as a strong argument in favour of the

view that they are due to a fall of the local level of the sea-surface from the disappearance or diminution of former ice-caps. That some at least of the raised beaches in these regions may be due to this cause may be granted. The gradual rise of level of the beaches when traced up the fjords, which has been repeatedly asserted for some districts, would be the natural effect of the greater mass of ice in the interior. In the exploration of the lake regions of North America numerous instances have been described of a slope upward of the former water-levels towards the main ice-fields. A remarkable example is furnished by the terraces of the vanished glacial sheet of water called Lake Agassiz which once filled the basin of the Red River of the North. Mr. Warren Upham has found that these ancient lines of water-level gradually rise from south to north and from west to east, in the direction of the former ice-fields, the amount of slope ranging from zero to 1·3 feet per mile.[1] Mr. G. K. Gilbert has noticed a rise of as much as 5 feet in a mile among the old terraces of Lake Ontario.[2]

Raised beaches occur round many parts of the coast-line of Britain. De la Beche gave the accompanying view (Fig. 77) of a Cornish locality where the existing beach is flanked by a cliff of slate, *b*, continually cut away by the sea so that the overlying raised beach, *a*, *c*, will ere long disappear. The coast-line on both sides of Scotland is likewise fringed with raised beaches, sometimes four or five occurring above each other at heights of 25, 40, 50, 60, 75, and 100 feet above the present high-water mark.[3] Others are found on both sides of the English Channel.[4] The sides of the mountainous fjords of Northern Norway, up to more than 600 feet above sea-level, are marked with conspicuous lines of terraces (Fig. 78), which consist partly of beach deposits, partly of notches ("seter") cut out of rock, probably with the aid of drifting coast-ice.[5] Proofs of recent elevation of

[1] *B. U. S. G. S.* No. 39 (1887), pp. 18, 20.

[2] *Science*, i. p. 222.

[3] For accounts of some British raised beaches, see De la Beche, 'Report on Geology of Devon and Cornwall,' chap. xiii. ; C. Maclaren, 'Geology of Fife and the Lothians,' 1839 ; R. Chambers, 'Ancient Sea Margins'; Prestwich, *Q. J. G. S.* xxviii. p. 38, xxxi. p. 29, xlviii. (1892), p. 263 ; R. Russell and T. V. Holmes, *Brit. Assoc.* 1876, Sects. p. 95 ; Ussher, *Geol. Mag.* 1879, p. 166 ; A. Dunlop, *Q. J. G. S.* xlix. (1893), p. 523 ; A. R. Hunt, *Geol. Mag.* 1895, p. 405 ; R. Tiddeman, *op. cit.* 1900, pp. 441 and 528.

[4] On the raised beach of Sangatte, near Calais, see Prestwich, *B. S. G. F.* (3), viii. (1880), p. 547 ; on those of Finisterre, C. Barrois, *Ann. Soc. Géol. Nord.* ix. (1882).

[5] On the strand-lines and proofs of emergence in Scandinavia, see R. Chambers, 'Tracings of the North of Europe' (1850), p. 172 *et seq.* Bravais, 'Voyages de la Commission scientifique du Nord, &c.,' translated in *Q. J. G. S.* i. p. 534. Kjerulf, *Z. D. G. G.* xxii. p. 1 ; 'Die Geologie des süd. und mittl. Norwegen,' 1880, p. 7 ; *Geol. Mag.* viii. p. 74. S. A. Sexe, "On Rise of Land in Scandinavia," *Index Scholarum of University*, Christiania, 1872. H. Möhn, *Nyt. Mag. Nat.* xxii. p. 1. Dakyns, *Geol. Mag.* 1877, p. 72. K. Pettersen, *Arch. Math. Nat. Christiania*, 1878, p. 182, x. (1885) ; *Geol. Mag.* 1879, p. 298 ; *Tromsö Museums Aarshefter*, iii. 1880 ; *Sitzb. Akad. Wien*, xcviii. (1889), p. 97. Lehmann, 'Ueber-ehemalige Strandlinier, &c.,' Halle, 1879 ; *Zeitsch. ges. Naturwiss.* 1880, p. 280. A. G. Högbom, *Geol. För. Förhandl. Stockholm*, ix. (1887), p. 19. C. Sandler, *Petermann's Mittheil.* xxxvi. (1890), pp. 209, 235. De Geer, *Geol. Fören. Stockholm*, x. (1888), p. 366 (with a map of isobasic lines for Scandinavia) ; xi. (1890), p. 61; xiv. (1892), p. 72 ; xv. (1893), pp. 77, 378 ; xvi. (1894), p. 639 ; xx. (1898), p. 369 ; *Sverig. Geol. Undersök.* No. 141 (1894), p. 15. 'Om Skandinaviens geograph. Utveckling' (with 6 maps), Stockholm, 1896. A. Nathorst, *Geol. Fören. Stockholm*, xii. (1890), p. 30 ; 'Sveriges Geologi,' p. 279. Sieger, *Zeitsch. Ges. Erdkund.*, Berlin, xxviii. (1893), pp. 1-106, 393-498. H. Berghell, *Fennia.* xiii. (1896). A. Badoureau, *Ann. des Mines*, 1894, pp. 239-275. W. Ramsay, *Fennia*, xii. (1896). A. Helland, *Norges Geol. Undersög.* No. 28, Aarbog 1900. H. Reusch, 'Folk og Natur i Finmarken,' Christiania, 1895, pp. 8, 13, 60, 64, 130. A. Hollender, *Geol. Fören. Stockholm*, xxiii. (1901), p. 231. A. Strahan, *Q. J. G. S.* liii. (1897),

the shores of the Mediterranean are furnished by raised beaches at various heights above the present water-level. Stratified sands containing recent marine-shells are found up to a height of 700 feet at Gibraltar.[1] In Corsica raised beaches have been noted at heights of from 15 to 20 metres.[2]

On the west coast of South America, lines of raised terrace containing recent shells have been traced by Darwin as proofs of a great upheaval of that part of the globe in modern geological time. The terraces are not quite horizontal, but rise towards the south. On the frontier of Bolivia, they occur at from 65 to 80 feet above the existing sea-level, but nearer the higher mass of the Chilian Andes they are found at 1000, and near Valparaiso at 1300 feet. That some of these ancient sea-margins belong to the human period was shown by Mr. Darwin's discovery of shells with bones of birds, ears of maize, plaited reeds and cotton thread, in one of the terraces opposite Callao at a height of 85 feet.[3] Raised beaches occur in New Zealand, and indicate a greater change of level in the southern than in the northern part of the country.[4] It should be observed that this increased rise of the terraces polewards occurs both in the northern and southern hemispheres, and is another of the facts insisted upon by those who would explain the terraces by displacements of the sea rather than of the land.

The evidence furnished by strand-lines in favour of the view that the emergence of land has in the main, if not entirely, been due to uplift of the lithosphere, rather than to variations in the surface of the hydrosphere, is greatly strengthened by the proofs which have been obtained that the movement has not been uniform even within comparatively short distances. This important observation has been established by Baron De Geer and other observers in the south-east of Scandinavia and the southern half of the Gulf of Bothnia. It has there been ascertained that the land has been upraised with a maximum elevation rather more than 1000 feet in the centre of the peninsula. De Geer has traced lines of equal deformation round this centre, and has found that these lines (*isobases*) group themselves in concentric circles, showing a tolerably regular decrease in height in every direction toward the peripheral part of the region until the line for zero is reached, outside of which no sign of upheaval is to be found.[5] Further evidence to the same effect is supplied by Dr. Helland, who has found by careful measurement in the Tromsö district that the two raised beaches so well displayed there have a seaward inclination, which in the case of the upper beach amounts to about three minutes, and in the lower to about one minute. The dip is nearly at right angles to the trend of the coast, so that it veers from a westerly direction in the south to northerly in the north. The uplift was evidently diminishing in rate, as shown by the dip being three times greater in the older terrace than in the younger.[6]

Further support of the view that the movement has had its origin in the land and not in the sea, is supplied by the observations of De Geer on changes of level in the shore-lines around the inland lakes of Southern Sweden. He has obtained evidence that those lakes which have their outlets in the direction away from the area of greatest

p. 137. J. H. Vogt, *Norges Geol. Undersög.* No. 29 (1900). The evidence of uprise is contested by Suess, who endeavours to prove that the terraces in Northern Scandinavia were made in ice-dammed fjords, and that the alleged proofs of uprise in the Gulf of Bothnia may be explained by changes in the level of the water due to climatological causes. See chaps. viii. and x. of the 'Antlitz der Erde' or 'Face de la Terre.'

[1] James Smith, *Q. J. G. S.* ii. (1846), p. 41. G. Maw, *Geol. Mag.* vii. (1870), p. 552. A. C. Ramsay and J. Geikie, *Q. J. G. S.* xxxiv. (1878), p. 521.

[2] *Bull. Soc. Géol. France* (3), iv. p. 86. On recent changes of level along the shores of Italy, see A. Issel, *Congr. Geog. Ital.* 1896, p. 165.

[3] 'Geological Observations,' chap. ix. See *Geol. Mag.* 1877, p. 28.

[4] Haast's 'Geology of Canterbury,' 1879, p. 366.

[5] See his papers on Scandinavian Strand-lines cited on the foregoing page.

[6] *Norges Geol. Undersög.* No. 28, Aarbog 1900.

elevation have undergone an uplift at their upper ends, deltas and lake deposits being now above the level of the water. The tilting of the ground around Lake Venern is estimated by him to have been about 13 metres towards the south. Some of the lakes have in this way been half emptied. On the other hand, those lakes which have their outflow towards the region of greatest elevation have undergone a submergence of their upper ends, which in the case of Lake Vettern is estimated at 10 metres.[1]

A similar inland warping has been detected in the interior of Canada and the United States in the region of the great lakes. It has there been ascertained that a movement of elevation is now going on to the north and north-east of the lakes, whereby the region occupied by these great bodies of water is being tilted towards the south-west.[2] Observations at intervals of from twenty to thirty-seven years indicate a mean rate of uplift of rather less than six inches in a century. The effect of this movement is to raise the shore-lines that lie to the north of the outlets, and to submerge those that lie to the south-west. As the whole body of Lake Huron is on the north side of the line (isobase) its shores are everywhere rising. In Lake Michigan, on the other hand, the shores of the southern half, which is situated to the south of the line, are steadily being submerged. The rise of the water at Milwaukee is estimated at 5 or 6 inches in a century, and at Chicago between 9 and 10 inches.

If this movement should continue, remarkable changes in the hydrography of the region will be brought about. At the present rate of tilting the water of Lake Michigan in some 500 or 600 years will have submerged the site of the present city of Chicago, and will have risen up to the level of the low watershed where the streams drain into the Mississippi. "In about 2000 years the discharge from Lake Michigan-Huron-Erie, which will then have substantially the same level, will be equally divided between the western outlet at Chicago and the eastern at Buffalo. In 2500 years the Niagara River will have become an intermittent stream, and in 3000 years all its water will have been diverted to the Chicago outlet, the Illinois River, the Mississippi River, and the Gulf of Mexico."[3]

Human Records and Traditions.—In countries which have been long settled by a human population, it is sometimes possible to prove, or at least to render probable, the fact of recent change of level by reference to tradition, to local names, and to works of human construction. Some of these sources of evidence have already been cited. Thus piers and harbours, if now found to stand above the upper limit of high-water, furnish indisputable evidence of an emergence of land since their erection. Numerous proofs of a recent change of level in the coast of the Arctic Ocean from Spitzbergen eastward have been observed. The shores of the Gulf of Bothnia, as above referred to, have undergone an appreciable uplift within the last century, at Stockholm the amount having been 48 centimetres (18½ inches). R. Sieger is of opinion that the elevation was at its maximum rate when Celsius began his survey in the early part of the eighteenth century, and that it has since then diminished. In Finmarken at Boxkop, Alten, an iron bolt fixed on the cliff, and said to have marked the upper limit of the zone of sea-weed at the time of the Bravais expedition (1844), is now 1·20 metre (nearly four feet) above the same limit at the present day.[4] At Spitzbergen, besides its raised beaches, bearing witness to previous elevations, small islands which existed two hundred years ago are now joined to larger portions of land. At Novaja

[1] *Sverig. Geol. Undersökn. Afhandl.* No. 141.

[2] J. W. Spencer, *Trans. Roy. Soc. Canada*, 1889, p. 132; *Amer. Journ. Sci.* xl. (1890), p. 443; xli. (1891), pp. 12-201; xlvii. (1894), p. 207; xlviii. (1894), p. 455. G. K. Gilbert, *National Geograph. Mag.*, Washington, September 1897; *18th Ann. Rep. U. S. G. S.* part ii. (1898), p. 601.

[3] G. K. Gilbert, *Nat. Geog. Mag. ut supra*, p. 247. J. W. Spencer, *Amer. Jour. Sci.* xlviii. (1894), p. 472.

[4] H. Reusch, 'Folk og Natur i Finmarken,' p. 8.

Zemlja, where six raised beaches were found by Nordenskjold, the highest being 600 feet above sea-level,[1] there seems to have been a rising of the sea-bottom to the extent of 100 feet or more since the Dutch expedition of 1594. On the north coast of Siberia the island of Diomida, observed in 1760 by Chalaourof to the east of Cape Sviatoj, was found by Wrangel sixty years afterwards to have been united to the mainland.[2]

§ 2. **Subsidence.**—It is more difficult to trace a downward movement of land, for the evidence of each successive sea-margin is carried down and washed away or covered up. The student will take care to guard himself against being misled by mere proofs of the advance of the sea on the land. In the great majority of cases, where such an advance is taking place, it is due not to subsidence of the land, but to erosion of the shores. It is, indeed, the converse of the deposition above mentioned (p. 381) as liable to be mistaken for proof of upheaval. The results of mere erosion by the sea, however, and those of actual depression of the level of the land, cannot always be distinguished without some care. The encroachment of the sea upon the land may involve the disappearance of successive fields, roads, houses, villages, and even whole parishes, without any actual change of level of the land. Moreover, certain causes, referred to below, may come into operation to produce an actual submergence of land without any real subsidence of the land itself. The following kinds of evidence are usually cited to prove subsidence.

Submerged Forests.—As the land is brought within reach of the waves, and its characteristic surface-features are effaced, the submerged area may retain little or no evidence of its having been a land-surface. It will be covered, as a rule, with sea-worn sand or silt. Hence, no doubt, the reason why, among the marine strata which form so much of the stratified portion of the earth's crust, and contain so many proofs of depression, actual traces of land-surfaces are comparatively rare. It is only under very favourable circumstances, as, for instance, where the area is sheltered from prevalent winds and waves, and where, therefore, the surface of the land can sink tranquilly under the sea, that fragments of that surface may be preserved under overlying marine accumulations. It is in such places that "submerged forests" occur (Fig. 79). These are stumps of trees still in their positions of growth in their native soil, often associated with beds of peat, full of tree-roots, hazel-nuts, branches, leaves and other indications of a terrestrial surface. There is sometimes, however, considerable risk of deception in regard to the nature and value of such evidence of depression. Where, for instance, shingle or sand is banked up against a shore or river-mouth, considerable spaces may be enclosed and filled with fresh water, the bottom of which may be some way below high-water mark. In such lagoons terrestrial vegetation and débris from the land may be deposited. Eventually, if the protecting barriers should be cut away the tides may flow over the layers of terrestrial peat, giving a false appearance of

[1] *Nature*, xv. p. 123.

[2] Grad, *Bull. Soc. Géol. France*, 3rd ser. ii. p. 348. Traces of oscillations of level within historic times have been cited from the Netherlands, Flanders, and Upper Italy. *Bull. Soc. Géol. France*, 2nd ser. xix. p. 556; 3rd ser. ii. pp. 46, 222; *Ann. Soc. Géol. Nord.* v. p. 218. For alleged changes of level in the estuary of the Garonne, see Artigues, *Act. Soc. Linn. Bordeaux*, xxxi. (1876), p. 287; and Delfortrie, *ibid.* xxxii. p. 79. It must be admitted that some of the supposed proofs of such changes are inconclusive or even founded on erroneous observation and deduction. See the discussion of the evidence by Professor Suess in his work already quoted.

subsidence. Again, owing to removal of subterranean sandy deposits by springs, overlying peat-beds may sink below sea-level.[1] There can be little doubt that many of the submerged forests of western Europe, which have been cited as proofs of subsidence, are to be thus explained.

De la Beche has described, round the shores of Devon, Cornwall, and western Somerset, a vegetable accumulation, consisting of plants of the same species as those which now grow freely on the adjoining land, and occurring as a bed at the mouths of valleys, at the bottoms of sheltered bays, and in front of and under low tracts of land, of which the seaward side dips beneath the present level of the sea.[2] Over this submerged land-surface, sand and silt containing estuarine shells have generally been

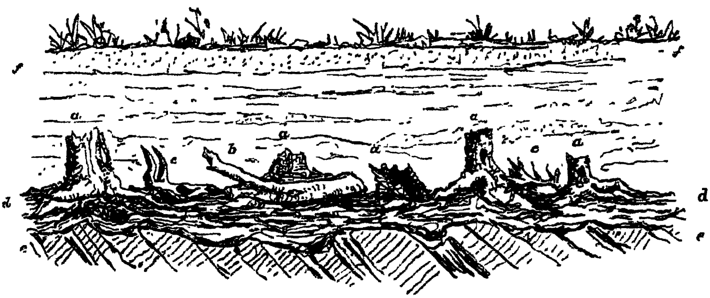


Fig. 79.—Section of Submerged Forest (*B.*).

A platform of older rocks (*e e*) has been covered with soil (*d d*) on which trees (*a a a a*) have established themselves. In course of time, after some of the trees had fallen (*b*), and a quantity of vegetable soil had accumulated, enclosing here and there the bones of deer and oxen (*c c*), the area sank, and the sea overflowing it threw down upon its surface sandy or muddy deposits (*f f*).

deposited, whence we may infer that, in the submergence, the valleys first became estuaries, and then sea-bays. If now, in the course of ages, a series of such submerged forests should be formed successively one over the other, and if, finally, they should, by upheaval of the sea-bottom, be once more laid dry, so as to be capable of examination by boring, well-sinking, or otherwise, they would prove a former long-continued depression, with intervals of rest. These intervals would be marked by the buried forests, and the progress of depression by the strata of sand and mud lying between them. In short, the evidence would be strictly on a parallel with that furnished by a succession of raised beaches as to a former protracted intermittent elevation.

Such a record of subsidence has been found at Barry on the north coast of the Bristol Channel, where four beds of peat full of terrestrial vegetation and clays containing fresh-water shells were met with in making a dock at that place. At least four terrestrial surfaces lie below mean sea-level, indicating a subsidence of not less than 55 feet since the earliest of them was overflowed by the sea.[3]

[1] See a paper by G. H. Morton (*Geol. Mag.* 1892, p. 482), in which he assigned the subterranean erosion of the glacial drift as a probable cause of submerged peat and forest-beds.

[2] "Geology of Devon and Cornwall," *Mem. Geol. Survey*. For further accounts of British submerged forests, see *Q. J. Geol. Soc.* xxii. p. 1; xxxiv. p. 447; *Geol. Mag.* vi. p. 76; vii. p. 64; iii. 2nd ser. p. 491; vi. pp. 80, 251. Mr. D. Pidgeon has argued in favour of the submerged forest of Torbay having been formed without subsidence of the land. *Quart. Journ. Geol. Soc.* xli. (1885), p. 9. See also W. Shone, *op. cit.* xlviii. (1892), p. 96.

[3] A. Strahan, *Q. J. G. S.* lii. (1896), p. 474. Many descriptions have been published of the "submerged forests" of the British coasts. Those of England are briefly referred to in Mr. H. B. Woodward's 'Geology of England and Wales.' Mr. Mellard Reade has noted

Along the coasts of Holland and the north of France, submerged beds of peat have been regarded as proofs of submergence during historic times. The amount of change varies considerably in different places, and here and there can hardly be appreciated. The sinking during the 350 years preceding 1850 is estimated to have amounted in the polders of Groningen to a mean annual rate of 8 millimetres.[1] In the north of France numerous examples of submerged forests have been observed. In 1846, in digging the harbour of St. Servan, near St. Malo, a Gaulish cemetery containing ornaments and coins, and resting on a still more ancient prehistoric cemetery, was met with at a level of 6 metres below the level of high tide, so that the submergence must have been at least to that extent.[2]

Coral-islands.—Evidence of widespread depression, over the area of the Pacific and Indian Oceans, has been adduced from the structure and growth of coral-reefs and islands. Mr. Darwin, many years ago, stated his belief that, as the reef-building corals do not live at depths of more than 20 to 30 fathoms, and yet their reefs rise out of deep water, the sites on which they have formed these structures must have subsided, the rate of subsidence being so slow that the upward growth of the reefs has on the whole kept pace with it.[3] More recent researches, however, show that the phenomena of coral-reefs are in some cases, at least, capable of satisfactory explanation without subsidence, and hence that their existence can no longer be adduced by itself as a demonstration of the subsidence of large areas of the ocean.[4] The formation of coral-reefs is described in Book III. Part II. Sect. iii., and Mr. Darwin's theory is there more fully explained.

Distribution of Plants and Animals.—Since the appearance of Edward Forbes's essay upon the connection between the distribution of the existing fauna and flora of the British Isles, and the geological changes which have affected that area,[5] much attention has been given to the evidence furnished by the geographical distribution of plants and animals as to geological revolutions. In some cases, the former existence of land now submerged has been inferred with considerable confidence from the distribution of living organisms, although, as Mr. Wallace has shown in the case of the supposed "Lemuria,"

evidence of oscillations of level in the neighbourhood of Liverpool, *Geol. Mag.* 1896, p. 488. The sunk forests of Central Scotland are discussed by me in the *Geol. Surv. Memoir* on Eastern Fife, 1902, p. 316.

[1] Lorié, *Archives du Musée Teyler*, sér. ii. vol. iii. part 5 (1890), p. 421. Lavaleye, 'Affaissement du Sol et envasement des Fleuves, survenus dans les temps historiques,' Brussels, 1859. Grad, *Bull. Soc. Géol. France*, ii. (3rd ser.), p. 46. Arends, 'Physische Geschichte der Nordseeküste,' 1833. Compare also R. A. Peacock on 'Physical and Historical Evidences of vast Sinkings of Land on the North and West Coasts of France, &c.,' London, 1868. For submerged peat-beds on French coast, see A. Gaspard, *Ann. Soc. Géol. Nord*, 1870-74, p. 40. On oscillations of French coast, T. Girard, *Bull. Soc. Géograph. Paris*, sér. 6, vol. x. p. 225; E. Delfortrie, *Act. Soc. Linn. Bordeaux.* sér. 4, vol. i. p. 79.

[2] Lorié, *ut supra*, p. 438. But see Suess, 'Antlitz der Erde,' ii. p. 547. Evidence of recent submergence has been collected in all parts of the globe, and reliance has been generally placed on the testimony of "submerged forests" in favour of subsidence of the land. From what has been said in the text, it is obvious that the evidence in each case must be tested with reference to the local conditions. Messrs. R. Etheridge, jun., and Edgeworth David have in this way critically examined the evidence of changes of level in New South Wales, and have described a proof of subsidence near Sydney: *Journ. Roy. Soc. N. S. Wales*, vol. xxx. (1896).

[3] See Darwin's 'Coral Islands,' Dana's 'Corals and Coral Islands,' and the works cited under "Coral-reefs," *postea*, p. 612. The various theories on the subject are discussed by R. Langenbeck in his 'Theorien über die Entstehung der Koralleninseln und Korallenriffe,' 1890.

[4] See *Proc. Roy. Phys. Soc. Edinburgh*, viii. p. 1.

[5] *Mem. Geol. Survey*, i. (1846), p. 336.

some of the inferences have been unfounded and unnecessary.[1] The present distribution of plants and animals is only intelligible in the light of former geological changes. As a single illustration of the kind of reasoning from present zoological groupings as to former geological subsidence, reference may be made to the fact, that while the fishes and mollusks living in the seas on the two sides of the Isthmus of Panama are on the whole very distinct, a few shells and a large number of fishes are identical; whence the inference has been drawn that though a broad water-channel originally separated North and South America in Miocene times, a series of elevations and subsidences has since occurred, the most recent submersion having lasted but a short time, allowing the passage of locomotive fishes, yet not admitting of much change in the comparatively stationary mollusks.[2]

Fjords.—An interesting proof of an extensive depression of the north-west of Europe is furnished by the fjords or sea-lochs by which that region is indented. A fjord is a long, narrow, and often singularly deep inlet of the sea, which terminates inland at the mouth of a glen or valley. The word is Norwegian, and in Norway fjords are characteristically developed. The English word "firth," however, is the same, and the western coasts of the British Isles furnish many excellent examples of fjords, such as the Scottish Loch Hourn, Loch Nevis, Loch Fyne, Gareloch; and the Irish Lough Foyle, Lough Swilly, Bantry Bay, Dunmanus Bay. Similar indentations abound on the west coast of British North America and of the South Island of New Zealand. Some of the Alpine lakes (Lucerne, Garda, Maggiore, and others), as well as many in Britain, are inland examples of fjords.

There can be little doubt that, though now filled with salt water, fjords have been originally land-valleys. The long inlet was first excavated as a valley or glen. The adjacent valley exactly corresponds in form and character with the hollow of the fjord, and must be regarded as merely its inland prolongation. That the glens have been excavated by subaerial agents is a conclusion borne out by a great weight of evidence, which will be detailed in later parts of this volume. If, therefore, we admit the subaerial origin of the glen, we must also grant a similar origin to its seaward prolongation. Every fjord will thus mark the site of a submerged valley. This inference is confirmed by the fact that fjords do not, as a rule, occur singly, but, like glens on land, lie in groups; so that, when found intersecting a long line of coast, such as that of the west of Norway or the west of Scotland, they show that the sea now runs far up and fills submerged glens.[3]

Human Constructions and Historical Records.—Should the sea be observed to rise to the level of roads and buildings which it never used to touch, should former half-tide rocks cease to be visible even at low water, and should rocks, previously above the reach of the highest tide, be turned first into shore-reefs, then into skerries and islets, we infer that the coast-line is sinking. Reference has above been made to proofs of this nature furnished by the west coast of Japan. Similar evidence is found in Scania, the most southerly part of Sweden. Streets, built of course above high-water mark, now lie below it, with older streets lying beneath them, so that the subsidence is of some antiquity. A stone, the position of which had been exactly determined by

[1] 'Island Life,' 1880, p. 394. In this work the question of distribution in its geological relations is treated with admirable lucidity and fulness.

[2] A. R. Wallace, 'Geographical Distribution of Animals,' i. pp. 40, 76.

[3] See on the submerged valleys of Scotland, A. G., 'Scenery of Scotland,' 3rd edit. 1900; those of South Wales, Devon, and Cornwall, Mr. Codrington, *Q. J. G. S.* liv. (1898), p. 251. The line of ancient submerged valleys can be traced by the soundings over the floor of the North Sea (J. Murray, *Min. Proc. Inst. Civ. Engin.* xx. 1861). Professor Hull has endeavoured to trace the prolongation of the river valleys of Western Europe across the submerged continental platform, and Mr. Hudleston has discussed the submarine topography of that region, *Geol. Mag.* 1899. pp. 97, 145.

Linnæus in 1749, was found after 87 years to be 100 feet nearer the water's edge.[1] The west coast of Greenland, for a space of more than 600 miles, is perceptibly sinking. It has there been noticed that, over ancient buildings on low shores, as well as over entire islets, the sea has risen. The Moravian settlers have been more than once driven to shift their boat-poles inland, some of the old poles remaining visible under water.[2] Historical evidence likewise exists of the subsidence of ground in Holland and Belgium. On the coast of Dalmatia, Roman roads and villas are said to be visible below the sea.[3]

§ 3. **Causes of Upheaval and Subsidence of Land.**[4]—While changes in the level of the land, whether sudden or secular, must be traced back mainly to consequences of the internal heat of the earth, there are various ways in which this cause may act. As rocks expand when heated, and contract on cooling, we may suppose that, if the crust underneath a tract of land has its temperature slowly raised, as no doubt takes place round areas of nascent volcanoes, while the magma is being squeezed upward, a gradual uprise of the ground above will be the result. The gradual transference of the heat to another quarter may produce a steady subsidence. Basing on the calculations of Colonel Totten, cited on p. 401, Lyell estimated that a mass of red sandstone one mile thick, having its temperature augmented 200° Fahr., would raise the overlying rocks 10 feet, and that a portion of the earth's crust of similar character 50 miles thick, with an increase of 600° or 800°, might produce an elevation of 1000 or 1500 feet.[5] But this computation, as Mr. Mellard Reade has pointed out, takes account only of linear expansion. If from any cause the mass of rock whose temperature was augmented could not expand horizontally, it would rise vertically; and unless some of the surplus volume could be disposed of by condensation of the rock, the uprise would be three times as much as the linear extension. Taking this view of the case, he finds that a mass of the earth's crust twenty miles thick, heated 1000° Fahr., and prevented from extending laterally, would rise 1650 feet.[6] He has accordingly sought in this cause an explanation of the origin of mountain ranges, and of the complicated geological structure which they present.

1 According to Erdmann, the subsidence has now ceased, or has even been exchanged for an upward movement (*Geol. För. Stockholm Förhandl.* i. p. 93). Nathorst also thinks that Scania is now sharing in the general elevation of Scandinavia (*ibid.* p. 281; 'Sveriges Geologi,' p. 267). It appears that the zero of movement now passes through Bornholm and Laaland.

2 These observations, which were generally accepted for more than a generation (*Proc. Geol. Soc.* ii. (1835), p. 208), have been called in question, but the alleged disproof is not convincing, and they are here retained as worthy of credence. See Suess, *Verhand. Geol. Reichsanstalt*, 1880, No. 11, and 'Antlitz der Erde,' ii. p. 415 *et seq.*

3 *Boll. Com. Geol. Ital.* 1874, p. 67.

4 Major Powell proposed the use of the term "diastrophism" to denote all the processes of deformation of the earth's crust. Elevation, subsidence, plication and fracture are all *diastrophic*. Mr. Gilbert has further subdivided diastrophism into *orogeny* or mountain-making and *epeirogeny* or continent-making. Orogenic movements are displayed in the narrower waves of uplift in the terrestrial crust, and are associated with the more energetic manifestations of diastrophism, while the epeirogenic, so far as known to us, are rather displayed in slow secular deformation of the crust. "Lake Bonneville," *Monog.* No. i. *U. S. G. S.* pp. 3, 340.

5 'Principles,' ii. p. 235.

6 Mellard Reade, 'Origin of Mountain Ranges' (1886), pp. 112, 114.

He conceives that such ranges can only take their rise in regions of copious sedimentation. As the successive layers of sediment are piled over each other for thousands of feet, the isogeotherms, or lines of equal subterranean temperature, move upward into them. The increase of temperature expands them in every direction in proportion to their extent and thickness. The tendency to lateral expansion is checked by the resistance of the part of the earth's crust lying beyond the locally heated area. The expanding mass is therefore forced to expend its energies within itself, and hence arise the plications, faults, thrust-planes and other structures characteristic of such uplifted ground. The cause thus appealed to must be admitted to exist and to possess some importance, though it may be incapable of achieving what is claimed for it.

Again, rocks expand by fusion and contract on solidification. Hence, by the alternate melting and solidifying of subterranean masses, upheaval and depression of the surface may possibly be produced (see pp. 399, 401, 408).

But processes of this nature probably only effect changes of level limited in amount and local in area. When we consider the wide tracts over which terrestrial movements are now taking place, or have occurred in past time, the explanation of them must manifestly be sought in some far more widespread and generally effective force in geological dynamics. It must be confessed, however, that no altogether satisfactory solution of the problem has yet been given, and that the subject still remains beset with many difficulties.

Professor Darwin, in one of his memoirs already cited (*ante*, p. 30), has suggested a possible determining cause of the larger features of the earth's surface. Assuming for his theory a certain degree of viscosity in the earth, he points out that, under the combined influence of rotation and the moon's attraction, the polar regions tend to outstrip the equator, and to acquire a consequent slow motion from west to east relatively to the equator. The amount of distortion produced by this screwing motion he finds to have been so slow, that 45,000,000 years ago a point in lat. 30° would have been $4\frac{3}{4}'$, and a point in lat. 60° $14\frac{1}{4}'$ farther west, with reference to the equator, than they are at present. This slight transference shows us, he remarks, that the amount of distortion of the surface strata from this cause must be exceedingly minute. But it is conceivable that, in earlier conditions of the planet, this screwing action of the earth may have had some influence in determining the surface features of the planet. In a body not perfectly homogeneous it might originate wrinkles at the surface running perpendicular to the direction of greatest pressure. "In the case of the earth, the wrinkles would run north and south at the equator, and would bear away to the eastward in northerly and southerly latitudes, so that at the north pole the trend would be north-east, and at the south pole north-west. Also the intensity of the wrinkling force varies as the square of the cosine of the latitude, and is thus greatest at the equator and zero at the poles. Any wrinkle, when once formed, would have a tendency to turn slightly, so as to become more nearly east and west than it was when first made."

According to the theory, the highest elevations of the earth's surface should be equatorial, and should have a general north and south trend, while in the northern hemisphere the main direction of the masses of land should bend round towards north-east, and in the opposite hemisphere towards south-east. Professor Darwin thinks that the general facts of terrestrial geography tend to corroborate his theoretical views, though he admits that some are very unfavourable to them. In the discussion of such a theory, however, we must remember that the present mountain chains on the earth's surface are not aboriginal, but arose at many successive and widely separated epochs. Now it is quite certain that the younger mountain chains (and these include the loftiest on the surface of the globe) arose, or at least received their chief upheaval, during the Tertiary periods—a comparatively late date in geological history. Unless we are to enlarge enormously the limits of time which physicists are willing to concede for the evolution of the whole of that history, we can hardly suppose that the elevation of the great mountain chains took place at an epoch at all approaching an antiquity of 45,000,000 years. Yet, according to Professor Darwin's showing, the superficial effects of internal distortion must have been exceedingly minute during the past 45,000,000 years. We must either therefore multiply enormously the periods required for geological changes, or find some cause which could have elevated great mountain-chains at more recent intervals.

But it is well worth consideration whether the cause suggested by Professor Darwin may not have given their initial trend to the masses of land, so that any subsequent wrinkling of the terrestrial surface, due to any other cause, would be apt to take place along the original lines. To be able to answer this question, it is necessary to ascertain the dominant line of strike of the older geological formations. But information on this subject is still scanty. In north-western Europe, the prevalent line along which terrestrial plications took place during the earlier half of Palæozoic time was from S.W. or S.S.W. to N.E. or N.N.E.—the Caledonian chain of Professor Suess; and a similar trend may be recognised in the Eastern States of North America. In the later Palæozoic ages other plications took a general W.S.W. direction, from the mouth of the Shannon to that of the Loire, and ridged up the Old Red Sandstone and older Carboniferous formations (Armorican chain). But the trend of later movements followed still other lines, down to the youngest foldings of the Alps. The striking contradictions between the actual direction of so many mountain chains and masses of land, and what ought to be their line according to the theory, seem to indicate that while the effects of internal distortion may have given the first outlines to the land areas of the globe, some other cause has been at work in later times, acting sometimes along the original lines, more frequently oblique to or across them.

The cause to which most geologists are now disposed to refer the corrugations of the earth's surface is secular cooling and consequent contraction.[1] If our planet has been steadily losing heat by radiation into

[1] For criticisms of this view see Rev. O. Fisher's 'Physics of Earth's Crust,' 2nd edit. Major Dutton on "Greater Problems of Physical Geology," *Bull. Phil. Soc. Washington*

space, it must have progessively diminished in volume. The cooling implies contraction. According to Mallet, the diameter of the earth is less by at least 189 miles since the time when the planet was a mass of liquid.[1] But the contraction has not manifested itself uniformly over the whole surface of the planet. The crust varies much in structure, in thermal resistance, and in the position of its isogeothermal lines. As the hotter nucleus contracts more rapidly by cooling than the cooled and hardened crust, the latter must sink down by its own weight, and in so doing requires to accommodate itself to a continually diminishing diameter. The descent of the crust gives rise to enormous tangential pressures. The rocks are crushed, crumpled, and broken in many places. Subsidence must have been the general rule, but every subsidence would doubtless be accompanied with upheavals of a more limited kind. The direction of these upheaved tracts, whether determined, as Professor Darwin suggests, by the effects of the internal distortion, or by some original features in the structure of the crust, would be apt to be linear. The lines, once taken as lines of weakness or relief from the intense strain, would probably be made use of again and again at successive paroxysms or more tranquil periods of contraction. Mallet ingeniously connected these movements with the linear direction of mountain chains, volcanic vents, and earthquake shocks. If the initial trend to the land masses were given as hypothetically stated by Professor Darwin, we may conceive that after the outer parts of the globe had attained a considerable rigidity and could then be only slightly influenced by internal distortion, the effects of continued secular contraction would be seen in the intermittent subsidence of the oceanic basins already existing, and in the successive crumpling and elevation of the intervening stiffened terrestrial ridges.

This view, variously modified, has been widely accepted by geologists as furnishing an explanation of the origin of the upheavals and subsidences of which the earth's crust contains such a long record. But it is not unattended with objections. The difficulty of conceiving that a globe possessing on the whole a rigidity equal to that of glass or steel could be corrugated as the crust of the earth has been, has led some writers to adopt the hypothesis of an intermediate viscous layer between the solid crust and the solid nucleus (*ante*, p. 66), while others have suggested that the observed subsidence may have been caused, or at least aggravated, by the escape of vapours from volcanic orifices. But with various modifications, the main cause of terrestrial movements is still sought in secular contraction.

Some observers, following an original suggestion of Babbage,[2] have supposed that upheaval and subsidence, together with the solidification, crystallisation, and metamorphism of the layers of the earth's crust, may have been in large measure due to the deposition and removal of mineral matter on the surface. There can be no doubt that the lines of equal

xi. p. 52; also *Amer. Journ. Sci.* viii. (1874), p. 121. Mr. Mellard Reade, 'Origin of Mountain Ranges.'

[1] *Phil. Trans.* 1873, p. 205.

[2] *Journ. Geol. Soc.* iii. (1834), p. 206.

internal temperature (isogeothermal lines) for a considerable depth downward, follow approximately the contours of the surface, curving up and down as the surface rises into mountains or sinks into plains. The deposition of a thousand feet of rock will cause a corresponding rise in the isogeotherms (p. 393); and if we assume the average rise of temperature to be 1° Fahr. for every 50 feet, then the temperature of the crust immediately below this deposited mass of rock will be raised 20°. But masses of sediment of much greater thickness have been laid down, and we may admit that a much greater increase of temperature than 20° has been effected by this means. On the other hand, the denudation of the land must lead to a depression of the isogeotherms, and a consequent cooling of the upper layers of the crust.

It may be conceded that in so far as the internal structure of rocks may be modified by such progressive increase of temperature as would arise from superficial deposit, this cause of change must have a place in geological dynamics. But it has been urged that, besides this effect, the removal of rock by denudation from one area and its accumulation upon another affects the equilibrium of the crust; that the portions where denudation is active, being relieved of weight, rise, while those where deposition is prolonged, being on the contrary loaded, sink.[1] This hypothesis has recently been strongly advocated by some of the geologists who have explored the Western States and Territories of America, and who point in proof of its truth to evidence of continuous subsidence in tracts where there was prolonged deposition, and of the uprise and curvature of originally horizontal strata over mountain ranges like the Uinta Mountains in Wyoming and Utah, which have been for a long time out of water. There can be no doubt that the solid rocks at no great depth beneath the surface have reached the limit at which, under the same pressure, they would be crushed to powder above ground, and that they are thus in a state of what has been called "latent plasticity," ready to move or flow in any direction in which some escape from the pressure is possible. To suppose, however, that the removal and deposit of a few thousand feet of rock, such as the mass of a mountain belt like the Alps, should so seriously affect the equilibrium of the crust as to cause it to sink and rise in proportion, would evince an incredible degree of mobility in the earth which would surely be manifested in other directions. The series of gravity measurements carried on from the eastern coast of the United States to Salt Lake City in 1894, has shown that "the earth is able to bear on its surface greater loads than American geologists have been disposed to admit. They indicate that unloading and loading through degradation and deposition cannot be the cause of the continued rising of mountain ridges with reference to adjacent valleys, but that, on the contrary, the rising of mountain ridges or orogenic corrugation is directly opposed by gravity, and is accomplished by independent forces in spite

[1] Similarly it has been contended that the accumulation of a massive ice-sheet on the land would cause a depression of the terrestrial surface. N. S. Shaler, *Proc. Boston Nat. Hist. Soc.* xvii. p. 288. T. F. Jamieson, *Quart. Journ. Geol. Soc.* 1882, and *Geol. Mag.* 1882, pp. 400, 526. Fisher, 'Physics of Earth's Crust,' p. 223.

of gravitational resistance."[1] That there has always been the closest relation between upheaval and denudation on the one hand, and subsidence and deposition on the other, is undoubtedly true. But denudation has been one of the consequences of upheaval, and deposition has been kept up only by continual subsidence.[2] Two obvious objections to this doctrine of "isostasy" have been forcibly expressed by Mr. R. S. Woodward. "In a mathematical sense, this theory is in a less satisfactory state than the theory of contraction. As yet we can see only that isostasy is an efficient cause if once set in motion, but how it is started, and to what extent it is adequate, remain to be determined. Moreover, isostasy does not seem to meet the requirements of geological continuity, for it tends rapidly towards stable equilibrium, and the crust ought therefore to reach a state of repose early in geologic time. But there is no evidence that such a state has been attained, and but little if any evidence of diminished activity in crustal movements during recent geologic time. Hence we infer that isostasy is competent only on the supposition that it is kept in action by some other cause tending constantly to disturb the equilibrium which would otherwise result. Such a cause is found in secular contraction, and it is not improbable that these two seemingly divergent theories are really supplementary."[3]

We are concerned in the present part of this volume only with the surface features of the land in so far as they bear on questions of geological dynamics. The history of these features will be more conveniently treated in Book VII. after the structure and history of the crust have been described. Before quitting the subject, however, we may observe that the larger terrestrial features, such as the great ocean basins, the lines of submarine ridge surmounted here and there by islands chiefly of volcanic materials, the continental masses of land, and at least the cores of most great mountain chains, are in the main of high antiquity, stamped as it were from the earliest geological ages on the physiognomy of the globe, and that their present aspect has been the result not merely of original hypogene operations, but of long-continued superficial action by the epigene forces described in Book III. Part II.[4]

[1] G. K. Gilbert, *Journ. Geol.* iii. (1895), p. 333, and *Bull. Phil. Soc. Washington*, xiii. (1895), p. 31. This frank admission by one of the great upholders of "isostasy" in America is of value. Mr. Gilbert goes on to say that though the gravity measurements proved that the "law of isostasy" does not hold in the case of large mountain chains, they showed that it must obtain in regard to the greater features of relief.

[2] The term "isostasy," to denote the equilibrium of the crust adjusting itself to the effects of denudation on the one hand, and deposition on the other, was first proposed by Captain Dutton in the paper on problems of Physical Geology cited on p. 394.

[3] "Mathematical Theories of the Earth"—Vice-presidential Address to Mathematical Section of the American Association for Advancement of Science, August 1889. *Smithsonian Report* for 1890, p. 196.

[4] The antiquity of the continental elevations and oceanic depressions on the surface of the globe will be further considered in Book VII.

## Section iv. Hypogene Causes of Changes in the Texture, Structure, and Composition of Rocks.

The phenomena of hypogene action considered in the foregoing pages relate almost wholly to the effects produced at the surface. It is evident, however, that these phenomena chiefly arise from movements within or beneath the earth's crust, and must be accompanied by very considerable internal changes in the rocks which form that crust. We cannot, of course, witness any of these processes at work, and can only judge of their nature and results by their effects, which can be observed in the structures of the rocks. These effects will be described in a later portion of this volume (Book IV.), when the architecture of the crust is discussed. There is a certain amount of inconvenience in treating the causes of the changes before the effects produced by them have been considered. But to preserve the logical arrangement of the various departments of geological inquiry, the subject is most fitly taken here as a branch of hypogene geological dynamics. The student, however, is referred forward to the different divisions of Book IV. in which the structures are described at length, of which the causes are dealt with in the present section. It may be enough to remark generally that the rocks, subjected to enormous pressure, have been contorted, crumpled, and folded back upon themselves, as if thousands of feet of solid limestones, sandstones, and shales had been merely a few layers of carpet; they have been shattered and fractured; they have in some places been pushed far above their original position, in others depressed far beneath it: so great has been the compression which they have undergone that they have been made to flow as plastic masses, while their component particles have been rearranged and even crystallised. They may here and there have been reduced to actual fusion. They have been abundantly invaded by molten rock from below, in dykes and veins and huge masses of every size and shape. Moreover, enormous quantities of lava have been poured out over the surface in all great regions of the globe and in many successive geological periods from the earliest to the present, so that the crust of the earth has been to no inconsiderable extent built up of material directly supplied from the heated interior.

While these processes of subterranean change lie beyond our direct reach, and we can only reason regarding them from the changes which we see them to have produced, a good number are of a kind which can in some measure be imitated in laboratories and furnaces. It is not requisite, therefore, to speculate wholly in the dark on this subject Since the early and classic researches of Sir James Hall, great progress has been made in the investigation of hypogene processes by experiment. The conditions of nature have been imitated as closely as possible, and varied in different ways, with the result of giving us an increasingly clear insight into the physics and chemistry of subterranean geological changes. The following pages are chiefly devoted to an illustration of the nature of hypogene action, in so far as that can be inferred from the results of actual experiment. The subject may be conveniently

treated under three heads:—1, The effects of mere dry heat; 2, the influence of the co-operation of heated water; 3, the effects of compression, tension and fracture.[1]

## § 1. Effects of Heat.

The importance of heat among the transformations of rocks has been fully admitted by geologists, since it used to be the watchword of the Huttonian or Vulcanist school at the end of last century. Three sources of subterranean heat may have at different times and in different degrees co-operated in the production of hypogene changes—the original internal heat of the globe, the heat arising from chemical changes within the crust or beneath it, and the heat due to the transformation of mechanical energy in the crumpling, fracturing, and crushing of the rocks of the crust.

**Rise of Temperature by Subsidence.**—As stated above (pp. 393, 396), the mere recession of rocks from the surface owing to superposition of newer deposits upon them will cause the isogeotherms to rise—in other words, will raise the temperature of the masses so withdrawn. This can take place, however, to but a limited extent, unless combined with such depression of the crust as to admit of thick sedimentary formations. From the rate of increment of temperature downwards it is obvious that, at no great depth, the rocks must be at the temperature of boiling water, and that further down, but still at a distance which, relatively to the earth's radius, is small, they may reach and exceed the temperatures at which they would fuse at the surface. Mere descent to a depth of several thousand feet, however, will not necessarily result in any marked lithological change, as has been shown in the cases of the Nova Scotian and South Welsh coal-fields, where sandstones, shales, clays, and coal-seams can be proved to have been once depressed 8000 or 10,000 feet below the sea-level, under an overlying mass of rock, and yet to have sustained no more serious alteration than the partial conversion of the coal into anthracite. To a still greater depth must the Penokee series of Pre-cambrian rocks in the Lake Superior region have been depressed. These rocks are themselves 14,000 feet thick, and they were once covered by the Keweenawan series, which is estimated to have a thickness of 40,000 feet, so that some parts of the Penokee series may have been buried under 64,000 feet, or more

[1] Since the researches of Hall (*Trans. Roy. Soc. Edin.* iii. 1790, p. 8; v. 1798, p. 43; vi. 1812, p. 71; vii. 1812, pp. 79, 139, 169; x. 1825, p. 314) on fusion, rock plication, and the nature and behaviour of igneous rocks, much excellent work has been accomplished in experimental geology. The labours of the late Professor Daubrée have been especially fruitful. This distinguished chemist and geologist devoted much time to researches designed to illustrate experimentally the processes of geology. His numerous important memoirs appeared in the *Annales des Mines; Comptes rendus de l'Académie des Sciences, Paris; Bulletin de la Société géologique de France;* and other publications. But a few years before his death he collected and republished them as 'Études synthétiques de Géologie expérimentale,' 8vo, 1879—a storehouse of information. The admirable memoirs of Delesse in the same journals should also be studied; likewise the 'Geologische und geographische Experimente' of Professor E. Reyer (Leipzig, 1892-4). Professor Stanislas Meunier has published a volume under the title of 'Géologie expérimentale,' which is mainly devoted to the illustration of epigene processes.

than twelve miles, of rock. Yet the rocks have come up again to the surface comparatively unaltered, and still retaining the distinctly clastic characters of their sedimentary members, without the assumption of a crystalline or schistose structure.[1] In these cases the rocks may have been kept for a long period exposed to a temperature at least as high as that of boiling water. Such a temperature would have been sufficient to set some degree of internal change in progress, had any appreciable quantity of water been present; whence the absence of alteration may perhaps be explicable on the supposition that these rocks were comparatively dry (p. 409), so as to be depressed and re-elevated without any serious internal movement.

**Rise of Temperature by Chemical Transformation.**—To what extent this cause of internal heat may be operative, forms part of an obscure problem. But that the access of water from the surface, and the consequent hydration of previously anhydrous minerals, must produce local augmentation of temperature, cannot be doubted. The conversion of anhydrite into gypsum, which takes place rapidly in some mines, gives rise to an increase of volume of the substance (pp. 410, 453). Besides the remarkable manner in which the rock is torn asunder by minute clefts, crystals of bitter-spar and quartz are reduced to fragments.[2] The amount of heat evolved during this process is capable of measurement. The conversion of limestone into dolomite, on the other hand, which involves a diminution of volume, may likewise be made the subject of similar experimental inquiry. Experiments with various kinds of rocks, such as clay-slate, clay and coal, show that when these substances are reduced to powder and mixed with water, they evolve heat.[3]

**Rise of Temperature by Rock-crushing.**—A further store of heat is provided by the internal crushing of rocks during the collapse and re-adjustment of the crust. The amount of heat so produced has been made the subject of direct experiment. Daubrée has shown that, by the mutual friction of its parts, firm brick-clay can be heated in three-quarters of an hour from a temperature of 18° to one of 40° C. (65° to 104° Fahr.).[4] He found likewise that two pieces of marble rapidly rubbed the one against the other developed an increase of 4°·5 C. in one minute.

The most elaborate and carefully conducted series of experiments yet made in this subject are those of Mallet, already (p. 352) cited. He subjected 16 varieties of stone (limestone, marble, porphyry, granite and slate), in cubes averaging rather less than 1½ inches in height, to pressures sufficient to crush them to fragments, and estimated the amount of pressure required, and of heat produced. The following examples may be selected from his table:[5]—

[1] C. R. Van Hise, *10th Ann. Rep. U. S. G. S.* (1889), p. 457.

[2] The microscopic structure of the stages in the conversion of anhydrite into gypsum is described by F. Hammerschmidt, *Tschermak's Mineral. Mittheil.* v. (1883), p. 272.

[3] W. Skey, *Chem. News*, xxx. p. 290. The transformation of aragonite into calcite has been shown by Favre and Silbermann to give rise to a relatively large disengagement of heat. H. Le Chatelier, *Compt. rend.* (1893), p. 390.

[4] 'Géol. expérimentale,' p. 448 *et seq.*

[5] *Phil. Trans.* 1873, p. 187. *Phil. Mag.* July 1875.

| Rock. | Temperature (Fahr.) in 1 cubic foot of rock due to work of crushing. | Number of cubic feet of water at 32 deg. evaporated into steam at 212 deg. | Volume of ice at 32 deg. melted to water at 32 deg. by one volume of rock. |
|---|---|---|---|
| Caen Stone, Oolite | 8°·004 | 0·0046 | 0·04008 |
| Sandstone, Ayre Hill, Yorkshire | 47°·79 | 0·0234 | 0·2026 |
| Slate, Conway | 132°·85 | 0·07 | 0·596 |
| Granite, Aberdeen | 155°·94 | 0·072 | 0·617 |
| Scotch furnace-clay porphyry | 198°·97 | 0·083 | 0·724 |
| Rowley Rag (basalt) | 213°·23 | 0·109 | 0·925 |

Within the crust of the earth, there are abundant proofs of enormous stresses under which the rocks have been crushed. The weight of rock involved in these movements has often been that of masses at least two or three miles thick. We can conceive that the heat thus generated may have been sufficient to promote many chemical and mineralogical re-arrangements (especially with the co-operation of water, *postea*, p. 409), and, as Mallet maintained, may even have been here and there, if sufficiently rapid, enough for the actual fusion of the rocks by the crushing of which it was produced.

**Rise of Temperature by Intrusion of Erupted Rock.**—The great heat of lava, even when it has flowed out over the surface of the earth, has been already referred to, and some examples have been given of its effects (pp. 304, 309). Where it does not reach the surface, but is injected into subterranean rents and passages, it must effect considerable changes upon the rocks with which it comes in contact. That such intruded igneous rocks have sometimes melted down portions of the crust in their passage, can hardly be doubted. But probably still more extensive changes may take place from the exceedingly slow rate of cooling of erupted masses, and the consequently vast period during which their heat is being conveyed through the adjacent rocks. Allusion will be made in later pages to the observed amount of such "contact-metamorphism." (Book IV. Part VIII. § 1.)

**Expansion.**—The extent to which rocks are dilated by heat has been measured with some precision for various kinds of material, as shown in the subjoined table:—

| Rock. | Linear expansion for every 1° Fahr. | Authority. |
|---|---|---|
| Black marble, Galway, Ireland | $\cdot00000247 = \frac{1}{404858}$ | Adie, *Trans. Roy. Soc. Edin.* xiii. p. 366. |
| Grey granite, Aberdeen | $\cdot00000438 = \frac{1}{228310}$ | *Ibid.* |
| Slate, Penrhyn, Wales | $\cdot00000576 = \frac{1}{173611}$ | *Ibid.* |
| White marble, Sicily | $\cdot00000613 = \frac{1}{163132}$ | *Ibid.* |
| Red sandstone, Portland, Connecticut | $\cdot00000953 = \frac{1}{104932}$ | Totten, *Amer. Journ. Sci.* xxii. (1832), 136.[1] |

[1] For additional results, see Mellard Reade's 'Origin of Mountain Ranges' (1886), p. 109.

According to these data, the expansion of ordinary rocks ranges from about 2·47 to 9·53 millionths for 1° Fahr. Even ordinary daily and seasonal changes of temperature suffice to produce considerable superficial changes in rocks (see p. 434). The much higher temperatures to which rocks are exposed by subsidence within the earth's crust must have far greater effects. Some experiments by Pfaff in heating from an ordinary temperature up to a red heat, or about 1180° C., small columns of granite from the Fichtelgebirge, red porphyry from the Tyrol, and basalt from Auvergne, gave the expansion of the granite as 0·016808, of the porphyry 0·012718, of the basalt 0·01199.[1] The expansion and contraction of rocks by heating and cooling have been already referred to as possible sources of upheaval and depression (pp. 392, 396). Mr. Mellard Reade concludes from his experiments that the mean coefficient of expansion for various classes of rocks may be taken as $\frac{1}{100192}$ for each degree Fahr., which would be equivalent to an expansion of 2·77 feet per mile for every 100° Fahr.[2]

**Crystallisation.**—In the experiments of Sir James Hall, pounded chalk, hermetically enclosed in gun-barrels and exposed to the temperature of melting silver, was melted and partially crystallised, but still retained its carbonic acid. Chalk, similarly exposed, with the addition of a little water, was transformed to the state of marble.[3] These experiments have been repeated by G. Rose, who produced by dry heat from lithographic limestone and chalk, fine-grained marble without melting. The distinction of true marble is the independent crystalline condition of its component granules of calcite (Fig. 27). This structure, therefore, can be superinduced by heat under pressure. In nature, portions of limestone which have been invaded by intrusive masses of igneous rock, have been converted into marble, the gradations from the unaltered into the altered rock being distinctly traceable, as will be shown in subsequent pages.

**Production of Prismatic Structure.**—The long-continued high temperature of iron-furnaces has been observed to have superinduced a prismatic or columnar structure upon the hearth-stones, and on the sand in which these are bedded.[4] This fact is of interest in geology, seeing that sandstones and other rocks in contact with eruptive masses of igneous matter have at various depths below the surface assumed a similar internal arrangement (Book IV. Part VIII. § 1).

**Dry Fusion.**—In an interesting series of experiments already cited, the illustrious De Saussure (1779) fused some of the rocks of Switzerland and France, and inferred from them, contrary to the opinion previously expressed by Desmarest,[5] that basalt and lava have not been produced from granite but from hornstone (pierre de corne), varieties of "schorl," calcareous clays, marls, and micaceous earths, and the cellular varieties from different kinds of slate.[6] He observed, however, that the artificial

[1] *Z. D. G. G.* xxiv. p. 403.

[2] 'Origin of Mountain Ranges,' p. 110.

[3] *Trans. Roy. Soc. Edin.* vi. (1805), pp. 101, 121. See note 2 on p. 403.

[4] C. Cochrane, *Proc. Dudley Geol. Soc.* iii. p. 54.

[5] *Mém. Acad. Scien.* 1771, p. 273.

De Saussure, 'Voyages dans les Alpes,' edit. 1803, tome i. p. 178.

products obtained by fusion were glassy and enamel-like, and did not always recall volcanic rocks, though some exactly resembled porous lavas. Dolomieu (1788) also contended that as an artificially fused lava becomes a glass, and not a crystalline mass with crystals of easily fusible minerals, there must be some flux present in the original lava, and he supposed that this might be sulphur.[1]

Sir James Hall, about the year 1790, began an important investigation, in which he succeeded in reducing various ancient and modern volcanic rocks to the condition of glass, and in restoring them, by slow cooling, to a stony condition in which distinct crystals (probably pyroxene, olivine, and perhaps enstatite) were recognisable.[2] Gregory Watt afterwards obtained similar results by fusing much larger quantities of the rocks. In more recent years, this method of research has been resumed and pursued with the much more effective appliances of modern science, notably by Mitscherlich, G. Rose, C. Sainte-Claire Deville, Delesse, Daubrée, Friedel, Sarasin, Fouqué, Michel-Lévy, Doelter, Hussak, Vogt, Morozewicz and Schmutz.[3] It has been experimentally proved that all rocks undergo molecular changes when exposed to high temperature; that when the heat is sufficiently raised they become fluid; that if the glass thus obtained is rapidly cooled it remains vitreous; and that, if allowed to cool slowly, a more or less distinct crystallisation sets in, the glass is devitrified, and a lithoid product is the result.

A glass is an amorphous substance resulting from fusion, perfectly isotropic in its action on transmitted polarised light (p. 147). Its specific gravity is rather lower than that of the same substance in the crystallised condition. By being allowed to cool slowly, or being kept for some hours at a heat which softens it, glass assumes a dull, porcelain-like aspect. This devitrification possesses much interest to the geologist, seeing that many volcanic rocks, as has been already described (p. 148), present the characters of devitrified glasses. As we have seen, it consists in the appear-

[1] 'Îles ponces,' p. 8 *et seq.* At temperatures between 2000° and 3000° C., various metallic oxides are fused and crystallise. H. Moissan, *Compt. rend.* cxv. (1892), p. 1034.

[2] *Trans. Roy. Soc. Edin.* v. p. 43. He thus found the explanation of a structure which he had observed in the dykes that traverse the crater-wall of Somma, where their outer margins were in some cases vitreous, while the interior presented the usual lithoid character. He now saw that the glassy part had been rapidly chilled and consolidated by coming in contact with the cold walls of the fissures in the cone. The actual products obtained by Hall in his experiments have been microscopically examined by Fouqué and Michel-Lévy. *Comptes rend.* May 1881. For repetitions of his fusion of limestone see *op. cit.* cxv. (1892), pp. 817, 934, 1009, 1296.

[3] From this abundant literature the following references are selected:—Fridel and Sarasin, *Bull. Soc. Min. France*, ii. (1879), pp. 113, 158; Fouqué and Michel-Lévy, 'Synthèse des Minéraux et des Roches'; K. von Chrustschoff, *Bull. Acad. Imp. St. Pétersbourg*, xiii. (1890), p. 181; *Mélanges Geol. Acad. St. Pétersbourg*, 1892, p. 147; Doelter and Hussak, *Neues Jahrb.* 1884, pp. 18, 158; A. Becker, *Z. D. G. G.* xxxvii. (1885), p. 10; J. H. Vogt, *Zeitsch. prakt. Geol.* No. 1, 4, 7 (1893); J. Morozewicz, *op. cit.* xxiv. (1895), p. 281; *Neues Jahrb.* 1893, ii. p. 43; *Tschermak's Mittheil.* xviii. (1898), pp. 1-90, 105-240 (these last remarkably interesting papers have an additional value from the historical summary of previous research which they give).

ance of minute crystallites, and other imperfect or rudimentary crystalline forms, accompanied with an increase of density and diminution of volume. It must be regarded as an intermediate stage between the perfectly glassy and the crystalline conditions. Rocks exposed to temperatures as high as their melting-points fuse into glass which, in the great majority of cases, is of a bottle-green or black colour, the depth of the tint depending mainly on the proportion of iron. In this respect they resemble the natural glasses—pitchstones and obsidians. Microscopic investigation of such artificially fused rocks shows that, even in what seems to be a tolerably homogeneous glass, there are abundant minute hair-like, feathered, needle-shaped or irregularly aggregated bodies diffused through the glassy paste. These crystallites, in some cases colourless, in others opaque, metallic oxides, particularly oxides of iron, resemble the crystallites observed in many volcanic rocks (p. 148). They may be obtained even from the fusion of a granitic or granitoid rock, as in the well-known case of the Mount Sorrel syenite near Leicester, which, being fused and slowly cooled, yielded to Mr. Sorby abundant crystallites, including exquisitely grouped octohedra of magnetite.[1]

According to the observations of Delesse, volcanic rocks, when reduced to a molten condition, attack briskly the sides of the Hessian crucibles in which they are contained, and even eat them through. This is an interesting fact, for it helps to explain how some intrusive igneous rocks have come to occupy positions previously filled by sedimentary strata, and why, under such circumstances, the composition of the same mass of rock should be found to vary considerably from place to place.[2]

A series of elaborate and successful experiments regarding the fusion of igneous rocks has been made by MM. Fouqué and Michel-Lévy. These observers, by mixing the chemical elements, and, in other cases, the mineralogical constituents, of certain minerals and rocks, and fusing these in platinum crucibles in a gas-furnace, have been able to produce both rock-forming minerals, such as several felspars, augite, leucite, nepheline, and garnet, and also rocks possessing the composition and microscopic structure of augite-andesites, leucite-tephrites, and true basalts. By rapid cooling, they obtained an isotropic glass, often full of bubbles, and varying in colour with the nature of the mixture from which it was formed. Where the mixture contains the elements of pyroxene, enstatite, or melilite, it must be cooled very rapidly to prevent these minerals from partially crystallising out of the glass. Nepheline also crystallises

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[1] Zirkel, *Mik. Besch.* p. 92; Sorby, Address Geol. Sect. Brit. Assoc. 1880. On the microscopic structure of slags, etc., see Vogelsang's 'Krystalliten,' and an interesting account by M. Ch. Vélain of glasses obtained from the fire at the Odéon, Paris, in 1850, and from the fusion of the ashes of grasses, *B. S. G. F.* xiii. (1886), p. 297.

[2] *Bull. Soc. Géol. France*, 2nd ser. iv. 1382; see also *Trans. Edin. Roy. Soc.* xxix. p. 492. Morozewicz found the same difficulty in experimenting with much larger quantities of material, the clay crucibles of a glass-work being attacked by the molten solution. *Tschermak's Mittheil.* xviii. (1899), p. 18. In the experiments by Doelter and Hussak no change was observed in the porcelain crucibles in which basalt, andesite and phonolite were melted. *Neues Jahrb.* 1884, p. 19. Bischof has described a series of experiments on the fusion of lavas with different proportions of clay-slate. He found that the lava of Niedermendig, kept an hour in a bellows-furnace, was reduced to a black glassy substance without pores, and that a similar product was obtained even after 30 per cent of clay-slate had been added and the whole had been kept for two hours in the furnace. 'Chem. and Phys. Geol.' supp. (1871), p. 98.

easily. The felspars, on the other hand, pass much more slowly from the viscous to the crystalline condition. In these experiments, use was made of the law that the fusion-temperature of a crystallised silicate is usually higher than that of the same substance in the glassy state. Hence if such a glass be kept sufficiently long at a temperature slightly higher than that at which it softens, the most favourable conditions are obtained for the production of molecular arrangements and the formation of those crystalline bodies which can solidify in the midst of a viscous magma. The limits of temperature for the production of a given mineral must thus be comprised within the narrow range between the fusion-point of the mineral and that of its glass. By varying the temperature in the experiments, distinct minerals can be obtained from the same magma. Minerals such as olivine, leucite, and felspar, which solidify at higher temperatures than the others, appear first, and the later forms are moulded round them. Thus an artificial basalt, like a natural one, always shows that its olivine has crystallised first. By providing facilities for the crystallisation of the minerals in the inverse order of their fusibilities, the characters of naturally formed crystalline rocks can thus be artificially produced by simple igneous fusion.

Certain well-known facts which appear to militate against the principle of these experiments have been successively explained by MM. Fouqué and Michel-Lévy. Some minerals, very difficult to fuse, contain crystals of others which are easily fusible, as if the latter had crystallised first, as in the case of pyroxene enclosed within leucite. But in reality the pyroxene has slowly crystallised out of inclusions of the surrounding glass which were caught up in the leucite. Where the same silicates are found to have crystallised first in large and subsequently in smaller forms, they may reveal stages in the gradual cooling and consolidation of the mass, one set of crystals, for example, being formed in a lava while still within the vent of a volcano, and another during the more rapid cooling after expulsion from the vent.

The rocks obtained artificially by these observers are thus classed by them:—1. Andesites and andesitic porphyrites—from the fusion of a mixture of four parts of oligoclase and one of augite. 2. Labradorites and labradoric porphyrites—from the fusion of three parts of labrador and one of augite. 3. A microlitic rock formed of pyroxene and anorthite. 4. Basalts and labradoric melaphyres—from the fusion of a mixture of six parts of olivine, two of augite and six of labrador. 5. Nephelinites—from the fusion of a mixture of three parts of nepheline and 1·3 of augite. 6. Leucitites—from the fusion of nine parts of leucite and one of augite. 7. Leucite-tephrite—from the fusion of a mixture of silica, alumina, potash, soda, magnesia, lime, and oxide of iron, representing one part of augite, four of labrador, and eight of leucite. 8. Lherzolite. 9. Meteorites without felspar. 10. Meteorites with felspar. 11. Diabases and dolerites with ophitic structure. In these artificially produced compounds the most complete resemblance to natural rocks was observed, down even to the minutiæ of microscopic structure. The crystals and microlites ranged themselves exactly as in natural rocks, with the same distribution of vitreous base and vitreous inclusions. It is thus demonstrated that a rock like basalt may be produced in nature in the dry way, by a process entirely igneous.[1]

[1] See the work of Messrs. Fouqué and Michel-Lévy, 'Synthèse des Minéraux et des Roches,' 1882, from which the above digest of their researches is taken. Since this paragraph was written I have had the advantage of being shown by M. Michel-Lévy the original slides prepared from the products obtained by him and M. Fouqué, and I can entirely corroborate the results at which these observers have arrived. They have succeeded in imitating all the essential features of such rocks as basalt, down even into minute microscopic details. They have produced rocks, not only showing microlitic forms, but with crystals of the constituent minerals as definitely formed as in any natural lava. Indeed, it would be hardly possible to distinguish between one of their artifical products and many true lavas.

Another series of experiments was subsequently carried on by Messrs. Doelter and Hussak of Gratz, to determine the effect of immersing various minerals in molten basalt, andesite, or phonolite. Among the results obtained by them are the production of a granular structure ("corrosion border") in pyroxene and hornblende, especially on the exterior, as may be observed in the hornblende of recent eruptive rocks; the conversion of a hornblende crystal, which still retains its form, into an aggregate of augite prisms and magnetite, as observed also in some basalts; the conversion of garnet into various other minerals, such as meionite, melilite, anorthite, lime-olivine, lime-nepheline, specular iron, and spinel, the garnet itself never re-appearing in the molten magma.[1]

Detailed experiments on the artificial production of minerals and rocks by fusion were carried on by M. J. Morozewicz in Warsaw, from the end of the year 1891 to the beginning of 1897.[2] Employing a Siemens gas-furnace, as used for glass-making, he obtained a temperature of 1600° C., and was able to conduct the operations on a considerable scale, sometimes melting more than 100 pounds of material in the same crucible. After complete fusion the product was usually allowed slowly to cool and crystallise for a week or two, exceptionally for two months and a half. Besides obtaining thirty-four distinct minerals, he has succeeded in producing the following rocks—liparite, basalt-obsidian, enstatite-basalt, magma-basalt, augitite, melilite-basalt, hauynophyre, hauyn-basalt, cordierite-andesite, spinel-basalt, felspar basalt, nepheline-basalt, corundum-nephelinite, and an anorthite-nephelin compound containing corundum. Not less successful were the experiments in reproducing some of the distinctive structures of volcanic rocks. Among these, spherulitic, intersertal-glassy, microporphyritic, hyalopilitic, ophitic, and trachytic were observed, and the conditions in which they were respectively developed. Thus the spherulitic structure was obtained by supersaturating the compound with any one of its constituents and by rapid cooling. For the porphyritic structure also a high supersaturation is necessary, but with a slow crystallisation. The intersertal-glassy structure depends mainly upon a rapid crystallisation as the result of a quick lowering of the temperature. If some fused masses are long exposed to a lower temperature (500° C. or 600° C.), a granular structure is produced without a glassy base, but with rounded secretions, while the same magma at a higher temperature gives a microporphyritic structure. The fusions rich in alkali were usually found to give a glassy or intersertal-glassy structure; those rich in alkaline earths, on the other hand, were marked by their high capacity for crystallising. Thus the structure obtained in these experiments appears to be mainly the result of external conditions of crystallisation and of the chemical composition of the substance, both qualitatively and quantitatively.

M. Morozewicz concludes that the order of separation of the minerals from the molten magma principally depends on the relation between the quantities of the compounds present in the material. The same compound may, under identical conditions, separate out earlier or later in another form according to its quantity. Another obviously important condition is the solubility of the substance in the magma; the smaller the solubility, the greater will, of course, be the readiness of the substance to separate out. Temperature likewise plays an essential part in this separation of some compounds. Magnetite, for example, appears with difficulty to saturate a magma at a higher temperature than 1000° C.; anorthite crystallises more easily at 1000° and above, than about 700°.

Among the observations which have special interest in regard to their bearing on the history of eruptive rocks, is one regarding the influence of specific gravity in effecting to some extent a separation of the constituents of a magma. A mass weighing 100 lbs., and consisting mainly of an alkali-augite, presented a sharp difference between the density of its upper and that of its under part. The upper, with a specific gravity of 2·634, contained no magnetite; while in the lower, with a specific gravity of 2·996,

[1] *Neues Jahrb.* 1884, pp. 18, 158.

[2] See his papers cited on p. 403.

that mineral had accumulated in large quantity. It is, likewise, a familiar fact at the glass-works, that towards the bottoms of the crucibles the surplus lime accumulates and leads to devitrification by the development of wollastonite and diopside.[1]

It was long ago maintained by Élie de Beaumont that in the crystallisation of rocks certain gaseous constituents were present, such as fluorine, phosphorus, and boron, and played a large part in the development of the component minerals, and the production of the crystalline structure.[2] He named these substances "agents minéralisateurs," and his views regarding their influence have been confirmed by subsequent experiment.[3] Thus K. B. Schmutz melted a series of basic and acid rocks with definite quantities of chlorides of magnesium, sodium, calcium, and aluminium, fluorides of sodium, potassium and calcium, potassium tungstate, etc. He found that these substances lower the melting-point of the rocks or aid in the crystallisation of the constituent minerals, or even promote the formation of other minerals than those of the original rocks. The highly basic rocks can be more or less easily melted without the help of these reagents, but in the case of the more acid rocks experimented upon the addition of these substances was indispensable. It may be added that while in the glass of the cooled melted basic rocks most of the minerals had been reproduced and a product had been obtained comparable to known basic rocks, in no case were the structure and mineral composition of the acid rocks imitated. Usually the result was a dark obsidian like glass. The gneiss-granite of Ceslak, however, fused with sodium chloride and potassium-tungstate, gave a more crystalline product containing only a little glass ; but instead of the original minerals—quartz, albite, orthoclase, mica, apatite, hornblende, zircon, tourmaline and magnetite—those now obtained consisted of felspars, intermediate between albite and acid oligoclase, orthoclase, augite resembling diopside, and hexagonal plates of tridymite. The rock resembled an augite-trachyte.[4]

In the experiments carried on by M. Morozewicz a quantity of granite weighing about 2 lbs. from the Tatragebirge was melted. After five days a black glassy mass was obtained, in the upper part of which, still unmelted, white, cracked grains of quartz, partially changed into tridymite, were noticed, which, being lighter than the glass, had come to the top, the lower portion of the mass remaining quite free of them. The glass had so uniform a colour and aspect that its composition might have been expected to be the same throughout the whole mass. But so far from this was the case, that while the specific gravity (at 22° C.) of the original granite was 2·716, that of the lower part of the glass was 2·484, while that of the upper part was 2·2384. The alumina, iron-oxide, and alkaline earth were more abundant in the lower, while the silica was considerably greater in the upper.

In fine, while experiment has shown that certain eruptive rocks of the basic order, such as basalts and augite-andesites, may be produced by mere dry fusion, the acid rocks present difficulties which have as yet proved insuperable in the laboratory. It has been hitherto found impossible to reproduce by simple igneous fusion rocks with quartz, orthoclase, white mica, black mica, and amphibole. We may therefore infer that these rocks have been produced in some other way than by dry igneous fusion. The acid rocks, terminating in granite, form a remarkable series, regarding the origin of which our knowledge is still meagre.

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[1] To some of the questions here alluded to fuller reference will be made in Book IV., when the subject of the differentiation of igneous magmas is under consideration.

[2] "Sur les Émanations volcaniques et métallifères," *Bull. Soc. Géol. France*, iv. (1846). This admirable and exhaustive memoir, one of the greatest monuments of Élie de Beaumont's genius, should be consulted by the student. See also De Lapparent (*Bull. Soc. Géol. France*, xvii. (1889), p. 282) on the part played by mineralising agents in the formation of eruptive rocks.

[3] Particularly by Fouqué and Michel-Lévy and by P. Hautefeuille, *Compt. rend.* xc. (1880), p. 130 ; civ. (1887), p. 508.

[4] *Neues Jahrb.* 1897, ii. pp. 124-155.

**Contraction of Rocks in passing from a Glassy to a Stony state.**[1]—Reference has been made in the foregoing pages to the expansion of rocks by heat and their contraction on cooling; likewise to the difference between their volume in the molten and in the solid state. It would appear that the diminution in density, as rocks pass from a crystalline into a vitreous condition, is, on the whole, greater the more silica and alkali are present, and is less as the proportion of iron, lime and alumina increases. According to Delesse, granites, quartziferous porphyries, and such highly silicated rocks lose from 8 to 11 per cent of their density when they are reduced to the condition of glass, basalts lose from 3 to 5 per cent, and lavas, including the vitreous varieties, from 0 to 4 per cent.[2] More recently, Mallet observed that plate-glass (taken as representative of acid or siliceous rocks) in passing from the liquid condition into solid glass, contracts 1·59 per cent, 100 parts of the molten liquid measuring 98·41 when solidified; while iron-slag (having a composition not unlike that of many basic igneous rocks) contracts 6·7 per cent, 100 parts of the molten mass measuring 93·3 when cold.[3] Probably the most accurate determinations in this subject yet made are those carried out by C. Barus at the suggestion of the late Clarence King. He used diabase (*ante*, p. 79) having a mean density of 3·0178, and in a series of experiments reduced it to the condition of obsidian by fusing it in crucibles of clay and of platinum. He found that the glass solidifies at a temperature of 1095° C., and that the contraction on solidification may be estimated at 3 per cent. The density of the cooled glass proved to be 2·717, thus showing a volume increment of 10 per cent.[4] By the contraction due to such changes in the internal condition of subterranean masses of molten rock, minor oscillations of level of the surface may be accounted for. Thus, the vitreous solidification of a molten mass of siliceous rock 1000 feet thick might cause a subsidence of about 16 feet; while, if the rock were basic, the amount of subsidence might be 67 feet.

**Sublimation.**—It has long been known that many mineral substances can be obtained in a crystalline form from the condensation of vapours (pp. 269, 313). This process, called Sublimation, may be the result of the mere cooling and re-appearance of bodies which have been vaporised by heat and solidify on cooling, or of the solution of these bodies in other

[1] Contrary to the general opinion and the results obtained by other experimenters, Prof. F. Niess of Hohenheim came to the conclusion that rocks expand in solidification. *Program zur 70 Jahresfeier Akad. Würtemberg*, Stuttgart, 1889, cited by C. Barus in the paper quoted below.

[2] *Bull. Soc. Géol. France*, 1847, p. 1390. Bischof had determined the contraction of granite to be as much as 25 per cent (Leonhard and Bronn, *Jahrb.* 1841). The correctness of this determination was disputed by D. Forbes (*Geol. Mag.* 1870, p. 1), who found from his own experiments that the amount of contraction must be much less. The values given by him were still much in excess of those afterwards obtained with much care by Mallet. Compare O. Fisher, 'Physics of the Earth's Crust,' 2nd edit. p. 45, and Barus as cited below.

[3] *Phil. Trans.* clxiii. pp. 201, 204; clxv.; *Proc. Roy. Soc.* xxii. p. 328.

[4] "High Temperature Work in Igneous Fusion and Ebullition," *Bull. U. S. G. S.* No. 103 (1893).

vapours or gases, or of the reaction of different vapours upon each other. These operations, of such common occurrence at volcanic vents, and in the crevices of recently erupted and still hot lava-streams, have been successfully imitated by experiment. In the early researches of Sir James Hall on the effects of heat modified by compression, he obtained by sublimation "transparent and well-defined crystals," lining the unoccupied portion of a hermetically sealed iron tube, in which he had placed and exposed to a high temperature some fragments of limestone.[1] Numerous experiments have been made by Delesse, Daubrée, and others in the production of minerals by sublimation. Thus, many of the metallic sulphides found in mineral veins have been produced by exposing to a comparatively low temperature (between that of boiling water and a dull-red heat) tubes containing metallic chlorides and sulphide of hydrogen. By varying the materials employed, corundum, quartz, apatite, and other minerals have been obtained. It is not difficult, therefore, to understand how, in the crevices of lava-streams and volcanic cones, as well as in mineral veins, sulphides and oxides of iron and other minerals may have been formed by the ascent of heated vapours. Superheated steam is endowed with a remarkable power of dissolving that intractable substance, silica; artificially heated to the temperature of the melting-point of cast-iron, steam rapidly attacks silica, and deposits the mineral in snow-white crystals as it cools. Sublimation, however, can hardly be conceived as having operated in the formation of rocks, save here and there in the infilling of open fissures.

## § 2. Influence of Heated Water.

In the geological contest fought at the beginning of last century between the Neptunists and the Plutonists, the two great battle-cries were, on the one side, Water, on the other, Fire. The progress of science since that time has shown that each of the parties had some truth on its side, and had seized one aspect of the problems touching the origin of rocks. If subterranean heat has played a large part in the construction of the materials of the earth's crust, water, on the other hand, has performed a hardly less important share of the task. They have often co-operated together, and in such a way that the results must be regarded as their joint achievement, wherein the respective share of each can hardly be exactly apportioned. In Part II. of this book the chemical operation of infiltrating water, at ordinary temperatures at the surface, and among rocks at limited depths, is described. We are here concerned mainly with the work done by water when within the influence of subterranean heat, and the manner in which this work can be experimentally imitated.

**Presence of Water in all Rocks.**[2]—Besides its combinations in hydrous minerals, water may exist in rocks either (1) retained interstiti-

[1] *Trans. Roy. Soc. Edin.* vi. p. 110.

[2] The geological influence of water has been treated in a masterly way by Daubrée in his work, 'Les Eaux souterraines à l'Époque actuelle,' 2 vols. 1887; and 'Les Eaux souterraines aux Époques anciennes,' 1 vol. 1887.

ally among minute crevices, or (2) imprisoned within the microscopic cells of crystals.

(1.) By numerous observations it has been proved that all rocks within the accessible portion of the earth's crust contain interstitial water, or, as it is sometimes called, quarry-water (*eau de carrière*). This is not chemically combined with their mineral constituents, but is merely retained in their pores. Most of it evaporates when the stone is taken out of the parent rock and freely exposed to the atmosphere. The absorbent powers of rocks very greatly, and chiefly in proportion to their degree of porosity. Gypsum absorbs from about 0·50 to 1·50 per cent of water by weight; granite, about 0·37 per cent; quartz from a vein in granite, 0·08; chalk, about 20·0; plastic clay, from 19·5 to 24·5. These amounts may be increased by exhausting the air from the specimens and then immersing them in water.[1] No mineral substance is strictly impervious to the passage of water. The well-known artificial colouring of agates proves that even mineral substances, apparently the most homogeneous and impervious, can be traversed by liquids. In the series of experiments above referred to (p. 354), Daubrée has illustrated the power possessed by water of penetrating rocks, in virtue of their porosity and capillarity, even against a considerable counter-pressure of vapour; and, without denying the presence of original water, he concludes that the interstitial water of igneous rocks may all have been derived by descent from the surface. The masterly researches of Poiseuille have shown that the rate of flow of liquids through capillaries is augmented by heat. He proved that water at a temperature of 45° C. in such situations moves nearly three times faster than at a temperature of 0° C.[2] At the high temperatures under which the water must exist at some depth within the crust, its power of penetrating the capillary interstices of rocks must be increased to such a degree as to enable it to become a powerful geological agent.

(2.) Reference has already (p. 142) been made to the presence of minute cavities, containing water and various solutions, in the crystals of many rocks. The water thus imprisoned was obviously enclosed with its gases and saline solutions, at the time when these minerals crystallised out of their parent magma. The quartz of granite is usually full of such water-vesicles. "A thousand millions," says Mr. J. Clifton Ward, "might easily be contained within a cubic inch of quartz, and sometimes the contained water must make up at least 5 per cent of the whole volume of the containing quartz."

**Solvent Power of Water among Rocks.**—The presence of interstitial water must affect the chemical constitution of rocks. It is now well understood that there is probably no terrestrial substance which, under proper conditions, is not to some extent soluble in water. By an interesting series of experiments, made many years ago by W. B. and H. D.

[1] See an interesting paper by Delesse, *B. S. G. F.* 2me sér. xix. (1861-2), p. 65.

[2] *Comptes rendus* (1840), xi. p. 1048. Pfaff ('Allgemeine Geologie,' p. 141) concluded from calculations as to the relations between pressure and tension that water may descend to any depth in fissures and remain in a fluid state even at high temperatures.

Rogers, it was ascertained that the ordinary mineral constituents of rocks could be dissolved to an appreciable extent even by distilled water, and that the change was accelerated and augmented by the presence of carbonic acid.[1] Water, as pure as it ever occurs in a natural state, can hold in solution appreciable proportions of silica, alkaliferous silicates, and iron-oxide, even at ordinary temperatures. The mere presence, therefore, of water within the pores of subterranean rocks cannot but give rise to changes in the composition of these rocks. Some of the soluble materials must be dissolved, and, as the water evaporates, will be re-deposited in a new form.

**This Power increased by Heat.**—The chemical action of water is marked at ordinary and even at low temperatures. M. Lacroix, for example, has described the formation of zeolites by snow-water in the Pyrenees.[2] There can be no doubt, however, that the action is increased by heat. But a high temperature is not necessary for many important mineral re-arrangements. Daubrée has proved that very moderate heat, not more than 50° C. (122° Fahr.) has sufficed for the production of zeolites in Roman bricks by the mineral waters of Plombières.[3] He has experimentally demonstrated the vast increase of chemical activity of water with augmentation of its temperature, by exposing a glass tube containing about half its weight of water to a temperature of about 400° C. At the end of a week he found the tube so entirely changed into a white, opaque, powdery mass, as to present not the least resemblance to glass. The remaining water was highly charged with an alkaline silicate containing 63 per cent of soda and 37 per cent of silica, with traces of potash and lime. The white solid substance was ascertained to be composed almost entirely of crystalline materials, partly in the form of minute perfectly limpid bi-pyramidal crystals of quartz, but chiefly of very small acicular prisms of wollastonite. It was found, moreover, that the portion of the tube which had not been directly in contact with the water was as much altered as the rest, whence it was inferred that, at these high temperatures and pressures, the vapour of water acts chemically like the water itself.

**Co-operation of Pressure.**—The effect of pressure must be recognised as most important in enabling water, especially when heated, to dissolve and retain in solution a larger quantity of mineral matter than it could

[1] *Amer. Journ. Sci.* (2), v. p. 401. This subject is exhaustively treated by Daubrée in vol. ii. of the work cited on p. 409. He enumerates 48 elements which have been detected in natural waters or in their deposits. The alkaline reaction of many minerals which the brothers Rogers observed has recently been more especially tested by F. W. Clarke, and has been quantitatively determined by G. Steiger, *B. U. S. G. S.* No. 167, 1900, pp. 156, 159. It appears that the action of water is rapidly appreciable, and that at the end of a month the powdered minerals, consisting of common silicates, kept in water at a temperature of 70° Fahr. lost from 0·05 to 0·57 per cent of alkalies.

[2] *Compt. rend.* cxxiii. (1896), p. 761.

[3] 'Géologie expérimentale,' p. 462. The experiments of J. J. Waterston to determine the expansion of water showed, as far back as 1863, that hard German glass begins to whiten and cloud below 300° C., and becomes mottled with opaque patches. *Phil. Mag.* xxvi. (1863), p. 119.

otherwise do,[1] and also in preventing chemical changes which take place at once when the pressure is removed.[2] In Daubrée's experiments above cited, the tubes were hermetically sealed and secured against fracture, so that the pressure of the greatly superheated vapour had full effect. By this means, with alkaline water, he not only produced the two minerals above mentioned, but also felspar and diopside.

The compressibility of water above 100° C., and its solvent action on glass, have been recently investigated by C. Barus, who points out that as this action is accompanied by a contraction of the original bulk of silicate and water, it is presumably accompanied by an evolution of heat. "Hence," he remarks, "if water at a temperature above 200°, and under a pressure sufficient to keep it liquid, be so circumstanced that the heat produced cannot easily escape, the arrangement in question is virtually a furnace; and since such conditions are necessarily met with in the upper layers of the earth's crust, it follows that the observed thermal gradient (*i.e.* the increase of temperature in depth below the earth's surface) will be steeper than a gradient which would result purely from the normal distribution of terrestrial heat. In other words, the observed rate of increase of temperature with depth is too large, since it contains the effects of a chemical phenomenon superimposed upon the pure phenomenon of heat conduction."[3]

Applying the results obtained by experiment to the consideration of the crystalline rocks, we recognise better the value of the inference already stated, that the liquid carbon-dioxide enclosed in the minute pores of many of these rocks, such as granite, indicates the high pressure under which these masses solidified. Besides the pressure due to their varying depth from the surface, the rocks must have been subject to the enormous expansion of the superheated water or vapour which filled all their cavities, and sometimes, also, to the compression resulting from the secular contraction of the globe and consequent corrugation of the crust. Mr. Sorby inferred that in many cases the pressure under which granite consolidated must have been equal to that of an overlying mass of rock 50,000 feet or more (upwards of 9 miles) in thickness, while De la Vallée Poussin and Renard from other data deduced a pressure equal to 87 atmospheres (p. 145).

**Aquo-igneous Fusion.**—As far back as the year 1846, Scheerer observed that there exist in granite various minerals which could not have consolidated save at a comparatively low temperature.[4] He instanced especially gadolinites, orthites, and allanites, which cannot endure a higher temperature than a dull-red heat without altering their physical characters; and he concluded that granite, though it may have

[1] Sorby has shown that the solubility of all salts which exhibit contraction in solution is remarkably increased by pressure. *Proc. Roy. Soc.* (1862-63), p. 340.

[2] See Cailletet, *Naturforscher*, v.; Pfaff, *Neues Jahrb.* 1871; W. Spring, *Bull. Acad. Roy. Belgique*, 2nd ser. xlix. (1880), p. 369. Pfaff found that plaster does not absorb water under a pressure of 40 atmospheres.

[3] On the compressibility of liquids, *B. U. S. G. S.* No. 92 (1892), p. 84. On the aqueous fusion of glass, *Amer. Jour. Sci.* xli. (1891), p. 110; *Phil. Mag.* xlvii. (1899), pp. 104, 461.

[4] *Bull. Soc. Géol. France*, iv. p. 468.

possessed a high temperature, cannot have solidified from simple igneous fusion, but must have been a kind of pasty mass containing a considerable proportion of water. It is common now to speak of the "aquo-igneous" origin of some eruptive rocks, and to treat their production as a part of what are termed the "hydro-thermal" operations of geology.

Scheerer, Élie de Beaumont, and Daubrée have shown how the presence of a comparatively small quantity of water in eruptive igneous rocks may have contributed to suspend their solidification, and to promote the crystallisation of their silicates at temperatures considerably below the point of fusion and in a succession different from their relative order of fusibility. In this way, the solidification of quartz in granite after the crystallisation of the silicates, which would be unintelligible on the supposition of mere dry fusion, becomes explicable. The water may be regarded as a kind of mother-liquor out of which the silicates crystallise without reference to relative fusibility.

The researches of the late Professor Guthrie on the influence of water in lowering the fusing points of various substances have an important geological bearing. He showed that while the melting-point of nitre by itself is 320° C., an admixture of only 1·14 per cent of water reduced the temperature of fusion by 20°, while by increasing the proportion of water to 29·07 per cent he lowered the melting-point to 97·6°, and he concluded that "the phenomenon of fusion is nothing more than an extreme case of liquefaction by solution." He could see no reason why water should not exist even at the earth's centre, for even granting that it has a "critical temperature," still, "at high pressures it will be compressible as a vapour to a density at least as great as that of liquid water." He concluded that "water at a high temperature may not only play the part of a solvent in the ordinary restricted sense, but that there is in many cases no limit to its solvent faculty; in other words, that it may be mixable with certain rocks in all proportions; that solution and mixture are continuous with one another, in some cases at temperatures not above the temperature of fusion of those bodies *per se*." [1]

Professor Guthrie was disposed to doubt whether the replenishment of water by capillary descent from the surface was necessary for the production of these phenomena of fusion and volcanic eruption. Professor Daubrée's experiments, however, enable us to see how the supply of water may be kept up from superficial sources; while from those of Professor Guthrie we learn that when the descending water reaches masses of highly heated but still solid rock, it may allow them to pass into a fused condition and to exert a powerful expansive force on the overlying crust.

**Artificial Production of Minerals.**—As the result of experiments, both in the dry and moist way, various minerals have been produced in the crystalline form. Among the minerals successfully reproduced are quartz, tridymite, corundum, hæmatite, titaniferous iron, magnetite, spinel, pleonaste, hercynite, zircon, emerald, ruby, hornblende, olivine, augite, enstatite, hypersthene, diopside, wollastonite, melanite, melilite, several felspars, leucite, nepheline, hauyne, nosean, sodalite, meionite, petalite,

[1] *Phil. Mag.* xviii. (1884), p. 117.

several zeolites, dioptase, rutile, brookite, anatase, perowskite, sphene, calcite, aragonite, dolomite, witherite, siderite, cerusite, malachite, diaspore, vivianite, apatite, anhydrite, diamond, with many metallic ores.[1]

**Artificial Alteration of Internal Structures.**—Besides showing the solvent power of superheated water and vapour upon glass in illustration of what happens within the crust of the earth, Daubrée's experiments possess a high interest and suggestiveness in regard to the internal re-arrangements and new structures which water may superinduce upon rocks. Hermetically sealed glass tubes containing scarcely one-third of their weight of water, and exposed for several days to a temperature below an incipient red-heat, showed not only a thorough transformation of structure into a white, porous, kaolin-like substance, encrusted with innumerable bipyramidal crystals of quartz, like those of the drusy cavities of rocks, but had acquired a very distinct fibrous and even an eminently schistose structure. The glass was found to split readily into concentric laminæ arranged in a general way parallel to the original surfaces of the tube, and so thin that ten of them could be counted in a breadth of a single millimetre. Even where the glass, though attacked, retained its vitreous character, these fine zones appeared like the lines of an agate. The whole structure recalled that of some schistose and crystalline rocks. Treated with acid, the altered glass crumbled and permitted the isolation of certain nearly opaque globules and of some minute transparent infusible acicular crystals or microlites, sometimes grouped in bundles and reacting on polarised light. Reduced to thin slices and examined under the microscope with a magnifying power of 300 diameters, the altered glass presented: 1st, Spherulites, $\frac{5}{10}$ of a millimetre in radius, nearly opaque, yellowish, bristling with points which perhaps belong to a kind of crystallisation, and with an internal radiating fibrous structure (these resist the action of concentrated hydrochloric acid, whence they cannot be a zeolite, but may be a substance like chalcedony); 2nd, innumerable colourless acicular microlites, with a frequently stellate, more rarely solitary distribution, resisting the action of acid like quartz or an anhydrous silicate; 3rd, dark green crystals of pyroxene (diopside). Daubrée satisfied himself that these enclosures did not pre-exist in the glass, but were developed in it during the process of alteration.[2]

But beside the effects from increase of temperature and pressure, we have to take into account the fact that water in a natural state is never chemically pure. Rain, falling through the air, absorbs in particular oxygen and carbon-dioxide, and, filtering through the soil, abstracts more of this oxide as well as other results of decomposing organic

[1] See the works of Daubrée, Fouqué, Michel-Lévy, Morozewicz, and others above cited.

[2] 'Géol. expérim.' p. 158 *et seq.* The production of crystals and microlites in the devitrification of glass at comparatively low temperatures by the action of water is of great interest. The first observer who described the phenomenon appears to have been Brewster, who, in the second decade of last century, studied the effect upon polarised light of glass decomposed by ordinary meteoric action. (*Phil. Trans.* 1814; *Trans. Roy. Soc. Edin.* xxii. (1860), p. 607. See on the weathering of rocks, *postea*, p. 448 *et seq.*)

matter. It is thus enabled to effect numerous decompositions of subterranean rocks, even at ordinary temperatures and pressures. But as it continues its underground journey, and obtains increased solvent power, the very solutions it takes up augment its capacity for effecting mineral transformations. The influence of dissolved alkaline carbonates in promoting the decomposition of many minerals was long ago pointed out by Bischof. In 1857 Sterry Hunt showed by experiments that water impregnated with these carbonates would, at a temperature of not more than 212° Fahr., produce chemical reactions among the elements of many sedimentary rocks, dissolving silica and generating various silicates.[1] Daubrée likewise proved that in presence of dissolved alkaline silicates, at temperatures above 700° Fahr., various siliceous minerals, as quartz, felspar, and pyroxene, could be crystallised, and that at this temperature the silicates would combine with kaolin to form felspar.[2]

As already stated, various "mineralising agents" promote the crystal lisation of minerals. The presence of fluorine has been proved experimentally to have a remarkable action in facilitating some precipitates, especially tin-oxides, as well as in other parts of the mechanism of mineral veins.[3] Illustrations of the important part probably played by this element in the crystallisation of some minerals and rocks were obtained by Ste. Claire Deville and Hautefeuille, who by the use of compounds of fluorine produced such minerals as rutile, brookite, anatase and corundum in crystalline form.[4] Élie de Beaumont inferred that the mineralising influence of fluorine had been effective even in the crystallisation of granite. He believed that "the volatile compound enclosed in granite, before its consolidation contained not only water, chlorine and sulphur, like the substance disengaged from cooling lavas, but also fluorine, phosphorus and boron, whence it acquired much greater activity and a capacity for acting on many bodies on which the volatile matter contained in the lavas of Etna has but a comparatively insignificant action."[5] We have seen above that in recent fusion experiments these mineralising agents have been found eminently efficaceous.

## § 3. Effects of Compression, Tension, and Fracture.

Among the geological revolutions to which the crust of the earth has been subjected, its rocks have been in some places powerfully compressed; elsewhere they have undergone enormous tension, and almost everywhere they have been more or less ruptured. Hence internal structures have been developed which were not originally present in the rocks. These structures will be more properly considered in Book IV. We are here concerned mainly with the nature and operation of the agencies by which they have been produced.

1 *Phil. Mag.* xv. p. 68.

2 *Bull. Soc. Géol. France*, xv. (1885), p. 103.

3 First suggested by Daubrée, *Ann. des Mines* (1841), 3me sér. xx. p. 65.

4 *Compt. rend.* xlvi. p. 764 (1858); xlvii. p. 89; lvii. p. 648 (1865). Fouqué and Michel-Lévy, 'Synthèse des Minéraux et des Roches.'

5 *B. S. G. F.* iv. (1846), p. 1249.

The most obvious result of pressure upon rocks is consolidation, as where a mass of loose sand is gradually compacted into a more or less coherent stone, or where, with accompanying chemical changes, a layer of vegetation is compressed into peat, lignite or coal. The cohesion of a sedimentary rock may be due merely to the pressure of the superincumbent strata, but some cementing material has usually contributed to bind the component particles together. Of these natural cements the most frequent are peroxide of iron, silica, and carbonate of lime. Moderate pressure equally distributed over a rock presenting everywhere nearly the same amount of resistance will promote consolidation, but may produce no further internal change. Where the component particles are chiefly crystalline, pressure may induce a crystalline structure upon the whole mass, as recent experiments have shown.[1] If, however, the pressure becomes extremely unequal, or if the rock subjected to it can find escape from the strain in one or more directions, it may flow as a plastic mass, or may undergo shear in certain planes, or may be crumpled, or the limit of its rigidity may be passed and rupture may take place. Some consequences of these movements may be briefly alluded to here in illustration of hypogene action in dynamical geology.

(1) **Minor Ruptures and Noises.**—Among mountain-valleys, in railway tunnels through hilly regions, or elsewhere among rocks subjected to much lateral pressure, or where, owing to the removal of material by running water, and the consequent formation of cavities, subsidence is in progress, sounds as of explosions are occasionally heard. In many instances, these noises are the result of relief from great lateral compression, the rocks having for ages been in a state of strain, from which as denudation advances, or as artificial excavations are made, they are relieved. This relief takes place, not always uniformly, but sometimes cumulatively by successive shocks or snaps. Mr. W. H. Niles of Boston has described a number of interesting cases where the effects of such expansion could be seen in quarries; large blocks of rock being rent and crushed into fragments, and smaller pieces being even discharged with explosion into the air.[2] More recently Mr. A. Strahan has called attention to the occurrence of slickensided surfaces in the lead-mines of Derbyshire which on being struck or even scratched with a miner's pick break off with explosive violence, and he suggests that the spars and ores along those surfaces are in "a state of molecular strain, resembling that of the Rupert's Drop or of toughened glass, and that this condition of strain is the result of the earth movements which produced the slickensides."[3]

If such is the state of strain in which some rocks exist even at the surface or at no great distance beneath it, we can realise that at great depths, where escape from strain is for long periods impossible, and the compression of the masses must be enormous, any sudden relief from this strain may well give rise to an earthquake-shock (p. 370). A continued

[1] W. Spring, *Bull. Acad. Roy. Belg.* 1880, p. 375.

[2] *Proc. Boston Soc. Nat. Hist.* xviii. (1876), p. 272.

[3] *Geol. Mag.* 1887, p. 400. See also the same volume, pp. 511, 522, and *Amer. Journ. Sci.* xli. (1891), p. 409.

condition of strain must also influence the solvent power of water permeating the rocks (p. 411).

(2) **Consolidation and Welding.**—That pressure consolidates rocks is familiar knowledge. Loose sedimentary materials may by mere pressure be converted into more or less firm and hard masses. Experiments by W. Spring upon many substances in the state of powder have shown that under high pressure they become welded into solid substances.

Fig. 80.—Section of compressed Argillaceous Rock in which Cleavage-structure has been developed. Magnified. (Compare Fig. 265).

Fig. 81.—Section of a similar Rock which has not undergone this modification. Magnified.

Under a pressure of 6000 atmospheres, coal-dust becomes a brilliant solid block, taking the mould of the cavity in which it is placed, and thereby giving evidence of plasticity. Peat, in like manner, becomes a brilliant black substance in which all trace of the original structure is gone.[1]

(3) **Cleavage.**—Over extensive tracts of country a peculiar structure has been superinduced by powerful lateral pressure, especially upon fine-grained argillaceous rocks, which are then termed slates. They split along a set of planes which, as a rule, are highly inclined or vertical, and independent of the original bedding. Examined more minutely, it is found that their component particles, which in most cases have a longer and shorter

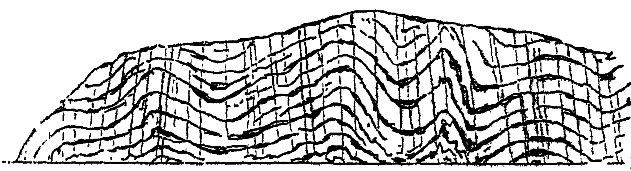
A  B

Fig. 82.—Curved Quartz Rock traversed by vertical and highly-inclined Cleavage. South Stack Lighthouse, Anglesea (*B.*).

axis, have grouped themselves with their long axes generally in one common direction, and parallel with the planes of fissility. An ordinary shale may present under the microscope such a structure as is shown in Fig. 81. But where it has undergone the change here referred to, it has acquired the structure represented in Fig. 80. Rocks which, having been thus acted on, have acquired this superinduced fissility, are said to be

[1] *Bull. Acad. Roy. Belg.* 1880, p. 325; and *ante*, p. 182.

cleaved, and the fissile structure is termed cleavage. In Fig. 82, for example, where the strata, at first in even parallel beds, have been subjected to great compression from the directions (A) and (B), the original planes of stratification are represented by wavy lines, and the new system of cleavage-planes by fine upright lines. The fineness of the cleavage depends in large measure upon the texture of the original rock. Sandstones, consisting as they do of rounded obdurate quartz-grains, take either a very rude cleavage (or jointing) or none at all. Fine-grained argillaceous rocks, composed of minute particles or flakes, that can adjust their long axes in a new direction, are those in which the structure is best developed. Even a compact homogeneous rock, such as a "felsite," may acquire a perfect cleavage structure. In a series of cleaved rocks, therefore, cleavage may be perfect in argillaceous beds (*b b*, Figs. 83 and 84),

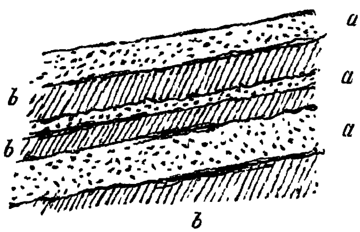



Fig. 83.

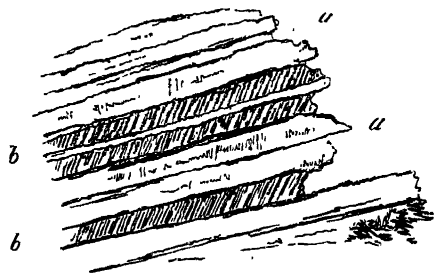



Fig. 84.

Dependence of Cleavage upon the grain of the rock (*B.*).

and imperfect or absent in interstratified beds of sandstone (*a a*, Fig. 83) or of limestone (as at Clonea Castle, Waterford, *a a*, Fig. 84).

That a cleavage may be produced in a mechanical way by lateral pressure has been proved experimentally by Sorby, who effected perfect cleavage in pipeclay through which scales of oxide of iron had previously been mixed.[1] Tyndall superinduced cleavage on beeswax and other substances by subjecting them to severe pressure. More recently, Fisher has proposed the view that in nature it is not to the pressure which plicated the rocks that cleavage is to be attributed, but to the shearing movements generated in large masses of rock left in a position too lofty for equilibrium.[2] If such, however, had been the origin of the structure, it is difficult to understand why there should be such a prevalent relation

[1] Hopkins, *Cambridge Phil. Trans.* viii. (1847), p. 455. D. Sharpe, *Q. J. G. S.* iii. (1846), p. 74; v. (1848), p. 111. Sorby, *Edin. New Phil. Journ.* lv. (1853), p. 137. J. Tyndall, *Phil. Mag.* xii. (1856), p. 35. W. King, *Roy. Irish Acad.* xxv. (1875), p. 605. The student will find interesting additions to our knowledge of the microscopic structure and the history of cleaved rocks in Mr. Sorby's address, *Q. J. G. S.* xxxvi. p. 72, and in Mr. Harker's able essay, *Brit. Assoc.* 1885, Reports, pp. 813-852. See also A. Daubrée, 'Géol. Expérimentale,' pp. 391-432. E. Jannettaz, *B. S. G. F.* ix. (1881), p. 196; xi. (1884), p. 211. G. F. Becker, *Bull. Geol. Soc. Amer.* iv. (1893), p. 13. C. R. Van Hise, *Journ. Geol.* iv. (1896), p. 449.

[2] *Geol. Mag.* 1884, p. 396.

between the strike and the cleavage; for if descent by gravitation were the main cause, we should expect to find the rocks sheared far more irregularly than even the most irregular disposition of cleavage. That in cleavage there has been a true distortion of the rocks is indubitable; and the amount of distortion may be ascertained by the extent of the alteration of shape of fossils (Figs. 85-88). Microscopic study of cleaved rocks shows that their fissility is not due merely to a re-arrangement of original clastic particles, but, perhaps in largest measure, to the development of new minerals, particularly varieties of mica, along the planes of cleavage. This relation is well seen in the folded and cleaved Devonian and Carboniferous rocks of S.W. Ireland and Cornwall, in the Carboniferous shales of Laval, Mayenne, and in the Jurassic and Eocene shales of the Alps.[1] Just as shales graduate into true cleaved slates, so slates by augmentation of their superinduced mica pass into phyllites, and these into mica-schists. The structure of districts with cleaved rocks is described in Book IV. Part V. p. 684.

(4) **Deformation.**—In the upper part of the earth's crust, where the rocks do not lie under a greater pressure than their crushing strength, they may give way to the pressure by fracturing or crushing. Beyond that limit of strength they probably lie in a more or less plastic condition, and, like cold solid metals in a hydraulic press, may be made to flow. Obvious proof of the powerful pressure to which rocks have been exposed is furnished by the way in which contiguous pebbles in a conglomerate have been squeezed into each other, and even sometimes have been elongated in a certain general direction. The coarseness of the grain of such rocks permits the effects of compression or tension to be readily seen. Similar effects may take place in fine-grained rocks and escape observation. Daubrée has imitated experimentally indentations produced by the contiguous portions of conglomerate pebbles.[2] Such indentations, particularly when the material is limestone or other tolerably soluble rock, may indeed have been to some extent produced by solution taking place most actively where pressure was greatest (p. 411). But of the indubitable evidences of crushing and deformation, even in what would be termed solid and brittle rocks, perhaps the most instructive and valuable are furnished by the remains of fossil plants and animals of which the unaltered shapes are well known. Where fossiliferous rocks have undergone a shear, the extent of this movement, as above remarked, can be measured in the resultant distortion of the

[1] Jannettaz, Renevier and Lory, *B. S. G. F.* ix. p. 649.

[2] *Comptes rendus*, xliv. p. 823; also his 'Géologie Expérimentale,' part i. sect. ii. chap. iii., where a series of important experiments on deformation is given. For various examples and opinions, see Rothpletz, *Z. D. G. G.* xxxi. p. 355. Heim, 'Mechanismus der Gebirgsbildung,' 1878, vol. ii. p. 31. Hitchcock, 'Geology of Vermont,' i. p. 28. *Proc. Bost. Soc. Nat. Hist.* vii. pp. 209, 353; xviii. p. 97; xv. p. 1; xx. p. 313. *Amer. Assoc.* 1866, p. 83. *Amer. Jour. Sci.* (2), xxxi. p. 372. Sorby, *Rep. Cardiff Nat. Soc.* 1873, p. 21. H. H. Reusch, 'Fossilien-fuhrend. kryst. Schiefer,' p. 25. On pitted pebbles in rocks, T. Mellard Reade, *Proc. Liverpool Geog. Soc.* sess. 1891-92; *Geol. Mag.* 1895, p. 341; Gresley, *op. cit.* p. 239.

fossils. In Figs. 85 and 87 drawings are given of two Lower Silurian fossils in their natural forms. In Fig. 86 a specimen of the same species of trilobite as in Fig. 85 is represented where it has been distorted during

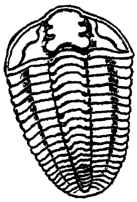


Fig. 85.—A Trilobite (*Calymene Blumenbachii*). natural shape.

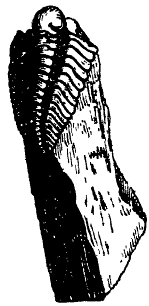


Fig. 86.—The same Trilobite, altered by Deformation—Lower Silurian, Hendre Wen, near Cerig y Druidion, North Wales (*B.*).

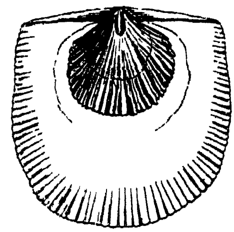


Fig. 87.—A Brachipod (*Strophomena expansa*), natural shape.

the shearing of the enclosing rock. In Fig. 88 four examples of the same shell as in Fig. 87 are shown greatly distorted by a strain which has elongated the rock in the direction *a b*.[1] Amorphous crystalline rocks (pegmatite, granite, diorite) have been so crushed as to acquire a schistose structure (pp. 246, 252, 255).

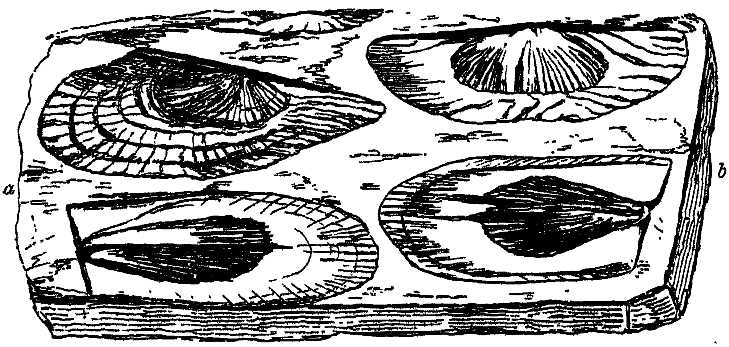



Fig. 88.—*Strophomena expansa*, altered by the deforming influence of Cleavage—Lower Silurian, Cwm Idwal, Caernarvonshire (*B.*).

Another illustration of the effects of pressure in producing deformation in rocks, is supplied by the so-called "lignilites," "epsomites," or "stylolites." These are cylindrical or columnar bodies varying in length up to more than four inches, and in diameter up to two or more inches. The sides are longitudinally striated or grooved. Each column, usually

[1] See D. Sharpe, *Q. J. G. S.* iii. (1846), p. 75. W. Hopkins, *Cambridge Phil. Trans.* viii. (1847), p. 466. S. Haughton, *Phil. Mag.* (1856), xii. p. 409. O. Fisher, *Geol. Mag.* 1884, p. 399. Harker, *Brit. Assoc.* 1885, Reports, p. 824.

with a conical or rounded cap of clay, beneath which a shell or other organism may frequently be detected, is placed at right angles to the bedding of the limestones or calcareous shales through which it passes, and consists of the same material. This structure has been referred by Professor Marsh to the difference between the resistance offered by the column under the shell, and by the surrounding matrix, to superincumbent pressure. The striated surface in this view is a case of "slickensides." The same observer has suggested that the more complex structure known as "cone-in-cone" may be due to the action of pressure upon concretions in the course of formation.[1]

The experiments of Tresca, Spring, Hallock, Adams and Nicolson and others[2] on the flow of solids have thrown considerable light upon the internal deformations of rock masses. Tresca proved that, even at ordinary atmospheric temperatures, solid resisting bodies like lead, cast-iron and ice may be so compressed as to undergo an internal motion of their parts, closely analogous to that of fluids. Thus, a solid jet of lead has been produced by placing a piece of the metal in a cavity between the jaws of a powerful compressing machine. Iron, in like manner, has been forced to flow in the solid state into cavities and take their shape. On cutting sections of the metals so compressed, their particles or crystals are found to have ranged themselves in lines of flow which follow the contour of the space into which they have been squeezed. Such experiments are of considerable geological interest. They illustrate how in certain circumstances, under great strain, rocks may not only be made to undergo internal deformation along certain shearing planes, as in cleavage, but may even be subjected to such stresses as to acquire a "shear-structure" resembling the fluxion-structure seen in rocks which have been truly liquid (p. 153). More recent experimental researches by Professor F. D. Adams and J. T. Nicolson have shown that when limestone or marble is submitted to differential pressures exceeding the elastic limit of the material, the rock undergoes permanent deformation. This change at ordinary temperatures is due partly to the production of a cataclastic or crushed structure, and partly to twinning and a gliding movement among the individual crystals of calcite, both of which effects can be seen among contorted limestones and marbles in nature. But when the temperature is 300° C. or 400° C. no cataclastic structure is observable, the whole internal movement being due to changes in the shape of the calcite crystals by

[1] *Proc. Amer. Assoc. Science*, 1867. Gümbel, *Z. D. G. G.* xxxiv. p. 642. W. S. Gresley, *Geol. Mag.* 1887, p. 17; *Q. J. G. S.* l. (1894), p. 731; liv. (1898), p. 196. J. Young, *Trans. Geol. Soc. Glasgow*, viii. (1885), p. 1; *Geol. Mag.* 1892, p. 138; also pp. 240, 278, 334.

[2] Tresca, *Comptes rend.* 1864, p. 754; 1867, p. 809; *Mém. Sav. Étrangers*, xviii. (1868), p. 733; xx. pp. 75, 137, 281, 617; *Inst. Mech. Engineers*, June 1867; June 1878. W. Spring, *Bull. Acad. Belg.* xlix. (1880), p. 323; ix. (3), 1885, p. 204. W. Hallock, *Bull. U. S. G. S.* No. 55 (1889), p. 67. F. D. Adams and J. T. Nicolson, *Geol. Mag.* 1897, p. 513; *Phil. Trans.* cxcv. (1901), pp. 363-401. W. C. Roberts-Austen, *Proc. Roy. Institution*, xi. (1886), p. 395. See also E. Reyer's 'Geologische und geographische Experimente,' Heft i.

twinning and gliding. The presence of water was not seen to exert any influence in the result.[1]

The experimental demonstration of the capacity of rocks to undergo internal molecular changes when exposed to severe differential pressures has much interest in regard to the origin of schistose and other structures in rocks which have manifestly suffered enormous compression. During the last twenty years observations have multiplied in all parts of the world in proof of the wide extent and great importance of such mechanical movements. An account of this evidence will be given in Book IV. Parts IV. to VIII.

(5) **Plication.**—On the assumption of a more rapid contraction of the inner hot nucleus of the globe, and the consequent descent of the cool outer shell, a subsiding area of the curved surface of the earth requires to occupy less horizontal space, and must therefore suffer powerful lateral compression. De la Beche long ago pointed out that if contorted and tilted beds were levelled out, they would require more room than can now be obtained for them without encroaching on other areas.[2] The magnificent example of the Alps brings before the mind the enormous extent to which the crust of the earth has in some places been compressed. According to the measurements and estimates of Professor Heim of Zurich, the diameter of the northern zone of the central Alps is only about one-half of the original horizontal extent of the component strata, which have been corrugated and thrown back upon each other in huge folds reaching from base to summit of lofty mountains, and spreading over many square miles of surface. He computes the horizontal compression of the whole chain at 120,000 metres; that is to say, that two points on the opposite sides of the chain have, by the folding of the crust that produced the Alps, been brought 120,000 metres, or 74 miles, nearer each other than they were before the movement.[3] Though the sight of such colossal foldings of solid sheets of rock impresses us with the magnitude of the compression to which the crust of the earth has been subjected, it perhaps does not convey a more vivid picture of the extent of this compression than is afforded by the fact that even in the minuter and microscopic structure of the rocks intricate puckerings are visible (Fig. 36). So intense has been the pressure, that even the tiny flakes of mica and other minerals have been forced to arrange themselves in complex, frilled, crimped, and goffered foldings. On an inferior scale, local compression and contortion may be caused by the protrusion of eruptive rocks. The characters of plicated rocks as part of the framework of the terrestrial crust are given in Book IV. Part IV.

As may be supposed, it is difficult to illustrate experimentally the processes by which vast masses of rock have been plicated and crumpled. The early devices of Sir James Hall, however, may be cited, from their interest as the first attempts to demonstrate the origin of the contortion of rocks. He placed layers of cloth under a weight, and by compressing

[1] *Phil. Trans.* cxcv. A (1901), pp. 363-401.

[2] 'Report, Devon and Cornwall' (1839), p. 187.

[3] 'Mechanismus der Gebirgsbildung,' ii. (1878), p. 213.

them from two sides produced corrugations closely resembling those of the Silurian strata of the Berwickshire coast (Fig. 89). Professor Favre of Geneva devised an experiment which more closely imitates the conditions in nature. Upon a tightly stretched band of india-rubber he placed various layers of clay, making them adhere to it as firmly as possible. By then allowing the band to contract he produced in the overlying strata of clay a series of contortions, inversions and dislocations which at once recalled those of a great mountain chain.[1] Mr. H. Schardt repeated the experiments, but with interstratifications of hard and soft clay and clay mixed with sand.[2] The subject was subsequently illustrated experimentally by Mr. H. M. Cadell, who, making use of plaster-of-Paris, with layers of sand, loam or clay, obtained results curiously like those exhibited by the crumpled and dislocated rocks of the N.W. Highlands of Scotland.[3] Dr. Reyer, who has devised a series of ingenious apparatus and methods for experimental research in geology, has devoted special attention to deformation and plication in illustration of the formation of mountains.[4] Mr. Bailey Willis has published an interesting series of experiments on the same subject, in which he used beeswax, hardening it with plaster-of-Paris or softening it with turpentine to obtain a range of quality from a brittle solid to a semi-fluid substance.[5]

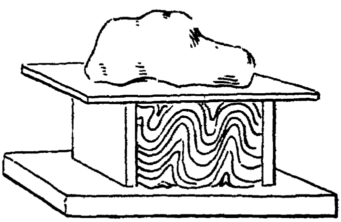


Fig. 89.—Hall's Experiment illustrating contortion.

(6) **Jointing and Dislocation.**—Almost all rocks are traversed by vertical or highly inclined divisional planes termed *joints* (Book IV. Part II.). These have been regarded as due in some way to contraction during consolidation (fissures of retreat); and this is no doubt their origin in innumerable cases. But, on the other hand, their frequent regularity and persistence across materials of very varying texture suggest rather the effects of internal pressure and movement within the crust. In an ingenious series of experiments, Daubrée has imitated joints and fractures by subjecting different substances to undulatory movement by torsion and by simple pressure, and he infers that they have been produced by analogous movements in the terrestrial crust.[6]

But in many cases the rupture of continuity has been attended with relative displacement of the sides, producing what is termed a *fault*. Daubrée also shows experimentally how faults may arise from the same

[1] *Nature*, xiv. (1878), p. 103.

[2] *Bull. Soc. Vaud. Sci. Nat.* xx. (1884), pp. 143-146.

[3] *Trans. Roy. Soc. Edin.* xxxvi. (1888), p. 337.

[4] See his 'Geologische und geographische Experimente,' already cited, especially parts i. and iv.

[5] *13th Ann. Rep. U. S. G. S.* (1894), p. 241. Compare Mr. Howe's experiments to illustrate the intrusion of igneous rocks, *op. cit.*, *21st Report* (1901), p. 291.

[6] 'Géol. Expérim.' part i. sect. ii. chap. ii. See W. King, *Roy. Irish Acad.* xxv. (1875), p. 605; and the theories of jointing given *postea*, p. 661.

movements as have caused joints, and from bending of the rocks. As the solid crust settles down, the subsidence, where unequal in rate, may cause a rupture between the less stable and more stable areas. When a tract of ground has been elevated, the rocks underlying it get more room by being pushed up, and are placed in a position of more or less instability. As they cannot occupy the additional space by any elastic expansion of their mass, they accommodate themselves to the new position by a series of dislocations.[1] Those segments having a broad base rise more than those with narrow bottoms, or the latter sink relatively to the former. Each broad-bottomed segment is thus bounded by two sides sloping towards the upper part of the block. The plane of dislocation is nearly always inclined from the vertical, and the side to which the inclination rises, and from which it "hades," is the upthrow side. Faults of this kind are termed *normal*, and are by far the most common in nature. In mountainous regions, however, instances frequently occur where one side has been pushed over the other, so that lower are placed above higher beds. Such a fault is said to be *reversed*. It indicates an upward thrust within the crust, and is often to be found associated with lines of plication. Where a sharp fold, of which one limb is pushed forward over the other, gives way along a line of rupture, the result is a reversed fault. The details of these features of geological structure are reserved for Book IV. Part VI. They are only noticed here, as their consideration forms one of the branches of dynamical geology.

## § 4. The Metamorphism of Rocks.

Another section of geological dynamics is devoted to the investigation of what is termed the "metamorphism" of rocks—that is, re-arrangement of their constituent materials, and most frequently the production of a new crystalline structure.[2] In this transformation the following conditions have been mainly operative :—(1) Temperature, from the lowest at which any change is possible up to that of complete fusion; (2) pressure, the potency of the action of heat being, within certain limits, increased with increase of pressure; (3) mechanical movements, which so often have induced molecular re-arrangements in rocks; (4) presence of water, usually containing various mineral solutions, whereby chemical changes can be effected which would not be possible in dry heat; (5) nature of the materials operated upon, some being much more susceptible of change than others.

A metamorphosed rock is one which has suffered such a mineralogical re-arrangement of its substance. It may or may not have been a crystalline rock originally. Any rock capable of alteration (and all rocks must be so in some degree) will, when subjected to the required conditions, be metamorphosed. The resulting structure, however, will, save in extreme cases, bear witness to the original character of the mass.

[1] See J. M. Wilson, *Geol. Mag.* v. p. 206; O. Fisher, *op. cit.* 1884.

[2] See A. Harker on the Physics of Metamorphism, *Geol. Mag.* vi. (1889), p. 15; J. W. Judd, *ibid.* p. 243; and Book IV. Part VIII. of this Text-book.

In some instances, the change has consisted merely in the re-arrangement or crystallisation of one mineral originally present, as in limestone converted into marble; in others, there has been a process of paramorphism, as where augite has been changed into hornblende in the alteration of dolerites into epidiorites; in others, the constituents have been forced by mechanical movements to range themselves in parallel laminæ, as where a diorite or pyroxenic rock becomes a hornblende-schist; in others, partial or complete transformation of the original constituents, whether crystalline or clastic, into new crystalline minerals has been accompanied by a complete re-crystallisation and change of structure in the rock. Quartzite is evidently a compacted sandstone, either hardened by mere pressure, or most frequently by the deposit of silica between its granules, or a slight solution of these granules by permeating water, so that they have become mutually adherent. A clay-slate is a hardened, cleaved, and partially metamorphosed form of muddy sediment, which on the one hand may be found full of organic remains, like any common shale, while on the other, by the appearance and gradual increase of some form of mica and other minerals, it may be traced becoming more and more crystalline, until it passes into phyllite, chiastolite-slate or some other schistose rock. Yet remains of fossils may be obtained even in the same hand-specimens with crystals of andalusite, garnet or other minerals. The calcareous matter of corals is sometimes replaced by hornblende, garnet and axinite, without deformation of the fossils.[1]

Since experiment has proved that in presence of water under pressure, even at comparatively low temperatures, mineral substances are vigorously attacked (p. 411), we may expect to find that as these conditions abundantly exist within the earth's crust, the rocks exposed to them have been more or less altered. A large proportion of the accessible crust consists of sedimentary materials which were laid down on the ocean-bottom, and which were still abundantly soaked with sea-water even after they had been covered over with more recent formations. The gradual growth and consolidation of submarine accumulations would deprive the lower strata of most of their original water, but some proportion of it would probably remain. If, according to Dana, the average amount of interstitial water in stratified rocks, at the earth's surface, such as limestones, sandstones and shales, be assumed to be 2·67 per cent, which is probably less than the truth, "the amount will correspond to two quarts of water for every cubic foot of rock."[2] There is certainly a considerable store of water ready for chemical action when the required conditions of heat and pressure are obtained. We must also remember that the water in which the sedimentary formations of the crust were formed, being mostly that of the ocean, already possessed chlorides, sulphates and other salts with which to begin its reactions. The inference may therefore be drawn, that rocks possessing not more than 3 per cent of interstitial water cannot be depressed to depths of several thousand feet

[1] *Ann. des Mines*, 5me sér. xii. p. 318. H. H. Reusch, 'Die Fossilien-führenden krystallinischen Schiefer von Bergen' (translated by R. Baldauf), Leipzig, 1883.

[2] 'Manual,' 3rd ed. (1880), p. 758.

beneath the level of the earth's surface, and undergo great pressure and crushing, without suffering more or less marked internal change or metamorphism.

For the sake of illustrating this department of dynamical geology in the present section of this volume, some typical examples of the nature of the changes involved will here be given. But the full discussion of the subject is reserved for Book IV. Part VIII., where the phenomena of "contact" and "regional" metamorphism as displayed among the rocks of the earth's crust will be described.

*Production of marble from limestone.*—One of the most obvious cases of alteration—the artificial conversion of limestone into crystalline saccharoid marble—has been already referred to (pp. 250, 402).[1] The calcite having undergone complete transformation, its original structure, whether organic or not, has been effaced, and a new structure has been developed, consisting of an aggregate of minute rounded grains, each with an independent crystalline arrangement (Fig. 27). The production of a crystalline structure in amorphous calcite may be effected by the action of mere meteoric water at or near the surface (pp. 160, 178, 475). But the generation of the peculiar granular structure of marble always demands heat and pressure, and probably usually the presence of water, though the details of the process, on the great scale, are still involved in obscurity. We know that where a dyke of basalt or other intrusive rock has involved limestone, it has sometimes been able to convert it for a short distance into marble. The heat (and perhaps the moisture) of the invading lava have sufficed to produce a granular structure, which even under the microscope is identical with that of marble. The conversion of wide areas of limestone into marble is a regional form of metamorphism, associated usually with the alteration of other sedimentary masses into schists, &c.

*Dolomitisation.*—Another alteration which, from the labours of Von Buch, received in the early decades of last century much attention from geologists, is the conversion of ordinary limestone into dolomite. Some dolomite appears to be an original chemical precipitate from the saline water of inland lakes and seas (p. 529). But calcareous formations due to organic secretions are often weakly dolomitic at the time of their formation, and may have their proportion of magnesium carbonate increased by the action of permeating water, as is proved by the conversion into dolomite of shells and other organisms, consisting originally of calcite or aragonite, and forming portions of what was no doubt originally a limestone, though now a continuous mass of dolomite. This change may have sometimes consisted in the mere abstraction of carbonate of lime from a limestone already containing carbonate of magnesia, so as to leave the rock in the form of dolomite; or probably more usually in the action of the magnesium salts of sea-water, especially the chloride, upon organically formed limestone; or sometimes locally in the action of a solution of carbonate of magnesia in carbonated water upon limestone, either magnesian or non-magnesian. Élie de Beaumont calculated that on the assumption that one out of every two equivalents of carbonate of lime was replaced by carbonate of magnesia, the conversion of limestone into dolomite would be attended with a reduction of the volume of the mass to the extent of 12·1 per cent. It is certainly remarkable in this connection that large masses of dolomite, which may be conceived to have once been limestone, have the cavernous, fissured structure which, on this theory of their origin, might have been looked for.

Dolomite has been produced both on a small and on a great scale. In the north of England and elsewhere, the Carboniferous limestone has been altered for a few feet or yards on either side of its joints into a dull yellow dolomite, locally termed "dunstone." Similar vertical zones of dolomite occur also in the Carboniferous limestone of Ireland. Harkness pointed out that the dolomite appears in vertical ribs where the rocks are

[1] See also "Marmarosis" in Book IV. Part VIII.

much jointed, and in beds where they have few or no joints.[1] No doubt percolating water has been the agent of change in the vertical zones. The beds, however, which in Ireland and elsewhere constitute important masses in the Carboniferous limestone, were more probably formed contemporaneously with the rocks among which they lie. They may have been deposited as limestone in shallow lagoons where the magnesian salts of concentrated sea-water would act upon them. Dolomite sometimes forms great ranges of mountains, as in the Eastern Alps, where it has by some writers been regarded as altered ordinary limestone. But these masses may have partly, at least, become dolomite at the beginning by the action of the magnesian salts of the concentrated waters of inland seas upon organic or inorganic calcareous deposits accumulated previous to the concentration, their metamorphism having consisted mainly in the subsequent generation of a crystalline structure analogous to that of the conversion of limestone into marble.[2]

*Conversion of vegetable substance into coal.*—Exposed to the atmosphere, dead vegetation is decomposed into humus, which goes to increase the soil. But sheltered from the atmosphere, exposed to the action of water, especially with an increase of temperature, and under some pressure, it is converted into lignite and coal. An example of this alteration has been observed in the Dorothea mine, Clausthal. Some of the timber in a long-disused level, filled with slate rubbish, and saturated with the mine-water from decomposing pyrites, was found to have a leathery consistence when wet, but, on exposure to the air, it hardened to a firm and ordinary brown coal, with the typical brown colour and external fibrous structure, and having the internal fracture of a black, glossy pitch-coal.[3] This change must have been produced within less than four centuries—the time since the levels were opened. According to Bischof's determinations the conversion of wood into coal may take place, 1st, by the separation of carbonic acid and carburetted hydrogen; 2nd, by the separation of carbonic acid, and the formation of water either from oxidation of hydrogen by meteoric oxygen, or from the hydrogen and oxygen of the wood; 3rd, by the separation of carbonic acid, carburetted hydrogen, and water.[4] The circumstances under which the vegetable matter now forming coal has been accumulated were favourable for this slow transmutation. The carbon-dioxide (choke-damp) of old coal-mines, and the carburetted hydrogen (fire-damp, $CH_4$) given off in such large quantities by coal-seams, are products of the alteration which would appear to be accelerated by terrestrial movements, such as those that compress and plicate rocks. During the process these gases escape, and the proportion of carbon progressively increases in the residue, till it reaches the most highly mineralised anthracite (p. 184), or may even pass into nearly pure carbon or graphite. In the coal-basins of Mons and Valenciennes, the same seams which are in the state of bituminous coal (*gras*) at the surface, gradually lose their volatile constituents as they are traced downward till they pass into anthracite. In the Pennsylvanian coal-field the coals become more anthracitic as they are followed into the eastern region, where the rocks have undergone great plication, and where, possibly during the subterranean movements, they were exposed to an elevation of temperature.[5] Daubrée has produced from wood, exposed to the

[1] *Q. J. G. S.* xv. p. 100.

[2] On dolomitisation, see L. von Buch, in Leonhard's *Mineralog. Taschenbuch*, 1824; Naumann's 'Geognosie,' i. p. 763; Bischof's 'Chemical Geology,' iii.; Élie de Beaumont, *Bull. Soc. Géol. France*, viii. (1836), p. 174; Sorby, *Brit. Assoc. Rep.* 1856, part ii. p. 77, and Address, *Q. J. Geol. Soc.* 1879. A full statement of the literature of this subject will be found in a suggestive memoir by C. Doelter and R. Hoernes, *Jahrb. Geol. Reichsanstalt*, xxv. The dolomite mountains of the Eastern Alps have been well described by Mojsisovics. See account of Triassic system, *postea*, Book VI.

[3] Hirschwald, *Z. Deutsch. Geol. Ges.* xxv. p. 364.

[4] Bischof, 'Chem. Geol.' i. p. 274.

[5] Daubrée, 'Géol. Expérim.' p. 463. Part of the framework below a steam-hammer has

action of superheated water, droplike globules of anthracite which had evidently been melted in the transformation, and which presented a close resemblance to the anthracite of some mineral veins.[1]

*Production of new minerals.*—Reference has above (p. 413) been made to the artificial formation of minerals in highly heated aqueous solutions. Such changes have been effected among the rocks within the crust, where doubtless water and heat have likewise been the chief agents in the process. Where metamorphism is well developed the chemical reactions which have been set up have given rise to more or less complete recombination of the chemical constituents of a rock. New minerals have thus been formed either entirely out of the materials already comprising the rock, or with some addition or replacement of substance introduced from without, by aqueous solution or otherwise. Carbonate of lime and silica are the two compounds that have been most abundantly brought by infiltration into rocks. Some of the commonest secondary minerals are micas; andalusite, chiastolite and garnet are also of frequent occurrence. (See Book IV. Part VIII.)

*Production of the schistose structure.*—All rocks are not equally permeable by water, nor is the same rock equally permeable in all directions. Among the stratified rocks especially, which form so large a proportion of the visible terrestrial crust, there are great differences in the facility with which water can travel, the planes of sedimentation, or those of cleavage or shearing where these have been developed, being naturally those along which water passes most easily. It is along these planes that differences of mineral structure and composition are ranged. Alternate layers of siliceous, argillaceous, and calcareous material vary in porosity and capability of being changed by permeating water. We may, therefore, expect that unless the original stratified structure has been effaced or rendered inoperative by any other superinduced structure, it will guide the metamorphic action of underground water, and will remain more or less distinctly traceable even after very considerable mineralogical transformations have taken place. Even without this guiding influence, superheated water can, to a certain extent, produce a schistose structure, parallel to its bounding surfaces, as Daubrée's experiments upon glass, above cited, have proved.

The stratified formations consist largely of silica, silicates of alumina, lime, magnesia, soda and potash, and iron-oxides. These mineral substances exist there as original ingredients, partly in recognisable worn crystals, partly in a granular or amorphous condition, ready to be acted on by permeating water under the requisite conditions of temperature and pressure. We can understand that any re-combination and re-crystallisation of the silicates will probably follow the laminæ of deposit or of cleavage, and that in this way a crystalline foliated structure may be developed. Round masses of granite erupted among Palæozoic rocks, instructive sections may be observed where a transition can be traced from ordinary unaltered sedimentary strata, such as sandstones, greywackes and shales containing fossils, into foliated crystalline rocks, to which the names of mica-schist and even gneiss may be applied. (Book IV. Part VIII.) Not only can the gradual change into a crystalline foliated structure be readily followed with the naked eye, but with the aid of the microscope the finer details of the alteration can be traced. Minute plates of some micaceous mineral and small concretions of andalusite, garnet, quartz, &c., may be observed to have crystallised out of the surrounding amorphous sediment. These, especially the mica, can be seen gradually to increase in size and number towards the granite, until the rock assumes a thoroughly foliated structure and passes into a true schist. Yet even in such a schist, traces of the original and durable water-worn quartz-granules may be detected.[2] As already stated (pp. 244, 246), foliation is a crystalline segregation of the mineral matter of a rock in certain dominant planes which may be those of original stratification,

been found after twenty years to be converted into lignite. F. Seeland, *Verh. Geol. Reichs.* 1883, p. 192.

[1] *Op. cit.* p. 177.

[2] Sorby, *Q. J. G. S.*, xxxvi. p. 82.

of joints, of cleavage, of shearing or of fracture.[1] Mr. Sorby has recognised foliation in three sets of planes even among the same rocks.[2]

Scrope many years ago called attention to the analogy between the foliation of schists and the ribbanded or streaked structure of trachyte, obsidian, and other lavas.[3] This analogy has even been regarded as an identity of structure, and the idea has found supporters that the schistose rocks have been in a condition similar to or identical with that of many volcanic masses, and have acquired their peculiar fissility by differential movements within the viscous or pasty magma, the solidified minerals being drawn out into layers in the direction of shearing. Daubrée, availing himself of the researches of Tresca on the flow of solids (p. 421), has endeavoured to imitate artificially some of the phenomena of foliation by exposing clay and other substances to great but unequal pressure.[4] That some of the lenticular wavy laminæ of different minerals in gneiss and other foliated rocks may be due to original segregation or flow in still unconsolidated igneous rock seems to be rendered highly probable by the curious analogies to this structure to be observed in the deeper parts of large intrusive bosses of rock, such as granite, diabase and gabbro (p. 256). These layers may thus be the remains of the oldest structure now retained by the gneiss. But subsequent pressure and deformation have frequently produced a foliation cutting obliquely across this original lamination and even entirely effacing it. (See Book IV. Part VIII. Sect. ii., and the section on pre-Cambrian rocks in Book VI.)

That the schistose structure has been largely induced by mechanical movements cannot be doubted. The evidence in the field and under the microscope has now rendered it certain that many rocks have been subjected to enormous mechanical stresses within the earth's crust; that they have yielded to the pressure both by disruption and by molecular shearing, that in some cases they have been crushed into minute fragments or dust, and have then been made to flow and to simulate the flow-structure of lava, while, in other cases, the crushed particles have crystallised into a granulitic structure, or the re-crystallisation has taken place along the flow-planes and has given rise to a perfect foliation. The action that produced cleavage, if further developed, might be accompanied with sufficient augmentation of temperature to permit of extensive mineralogical transformation along the cleavage-planes. But probably a rise of temperature was not essential. The conversion of pyroxene into hornblende, which has been observed in regions of crystalline schists, points indeed to a lower temperature than that required for the crystallisation of the original mineral.[5] A schistose structure of almost any degree of coarseness might conceivably be produced. A mixed rock, such as granite, has been converted into a foliated gneiss. Diorite, diabase, or gabbro has likewise by mechanical movement, with accompanying chemical and crystallographic transformation, been made to assume a schistose structure and pass into amphibolite-schist.

The study of metamorphism and metamorphic rocks leads us from unaltered mechanical sediments at the one end, into thoroughly crystalline masses at the other. We are presented with a cycle of change wherein the same particles of mineral matter pass from crystalline rocks into sedimentary deposits, then by increasing stages of alteration back into crystalline masses, whence, after being reduced to detritus and re-deposited in sedimentary formations, they may be once more launched on a similar series of transformations. The phenomena of metamorphism appear to be linked together with those of igneous action as connected manifestations of hypogene change.

[1] Darwin, 'Geological Observations,' p. 162. Ramsay, "Geology of North Wales," in *Memoirs of Geol. Survey*, iii. p. 182. [2] *Op. cit.* p. 84.

[3] 'Volcanoes,' pp. 140, 300. [4] 'Géologie Expérimentale,' p. 410.

[5] See G. H. Williams, *Amer. Journ. Sci.* xxviii. (1884), p. 259.

It is evident that while many of the dynamical processes of change among the rocks beneath the earth's surface can be successfully imitated artificially, and while such imitations are of the greatest value in affording a clearer perception of the nature and working of these processes, there remain difficulties which can probably never be overcome and which prevent some of the hypogene changes from ever being adequately illustrated by experiment. There are especially two respects in which human effort must obviously fail. We can never obtain pressures at all equal to those under which the rocks undergo mechanical and chemical changes in the deeper parts of the terrestrial crust. And even more out of our reach is the time that may be necessary for the accomplishment of these changes. With the highest temperatures and the most severe pressures we can command, our experiments must be performed in the merest infinitesimal fraction of the time taken by nature in the operations we try to imitate. A few hours or days or even months may be all the interval available to us. But the natural processes have extended over vast ages, and where they may seem to us feeble in their action, they have yet been able, by their uninterrupted continuity, to produce some of the most gigantic revolutions in the structure of the crust and the topography of the surface.

## PART II. EPIGENE OR SURFACE ACTION:

### *An Inquiry into the Geological Changes in progress upon the Earth's Surface.*

On the surface of the globe and by the operation of agents working there, the chief amount of visible geological change is now effected. This branch of inquiry is not involved in the preliminary difficulty, regarding the very nature of the agents, which attends the investigation of hypogene action. On the contrary, the surface agents are carrying on their work under our eyes. We can watch it in all its stages, measure its progress, and mark in many ways how well it represents similar changes which for long ages previously must have been effected by similar means. But in the systematic treatment of this subject, a difficulty of another kind presents itself. While the operations to be discussed are numerous and often complex, they are so interwoven into one great network that any separation of them under different subdivisions is sure to be more or less artificial, and is apt to convey an erroneous impression. While, therefore, under the unavoidable necessity of making use of such a classification of subjects, we must bear always in mind that it is employed merely for convenience, and that, in nature, superficial geological action must be viewed as a whole, since the work of each agent has close relations with that of the others and is not properly intelligible unless this connection be kept in view.

The movements of the air; the evaporation from land and sea; the fall of rain, hail and snow; the flow of rivers and glaciers; the tides, currents and waves of the ocean; the growth and decay of plants and animals, alike on land and in the depths of the sea—in short, the whole circle of movement, which is continually in progress upon the

surface of our planet—are the subjects now to be examined. It is desirable to adopt some general term to embrace the whole of this range of inquiry. For this end the word epigene may be used as a convenient term, antithetical to hypogene, or subterranean action.

The simplest arrangement of this part of Geological Dynamics will be into three sections:—

I. Air.—The influence of the atmosphere in destroying and forming rocks.

II. Water.—The geological functions of the circulation of water through the air and between sea and land, and the action of the sea.

III. Life.—The part taken by plants and animals in preserving, destroying, or originating geological formations.

The words destructive, reproductive and conservative, employed in describing the operations of the epigene agents, do not necessarily imply that anything useful to man is destroyed, reproduced or preserved. On the contrary, the destructive action of the atmosphere may cover bare rock with rich soil, while its reproductive effects may bury fertile soil under sterile desert. Again, the conservative influence of vegetation has sometimes for centuries retained as barren morass what might otherwise have become rich meadow or luxuriant woodland. The terms, therefore, are used in a strictly geological sense, to denote the removal and re-deposition of material, and its agency in preserving what lies beneath it.

## Section i. Air.

The geological action of the atmosphere arises partly from its chemical composition and partly from its movements. The composition of the atmospheric envelope has been already discussed (p. 36), and further information on this subject will be found under the head of Rain (p. 448). The movements of the atmosphere are due to variations in the distribution of pressure or density, the law being that air always moves vorticosely from where the pressure is high to where it is low. Atmospheric pressure is understood to be determined by two causes, temperature and aqueous vapour. Since warm air, being less dense than cold air, ascends, while the latter flows in to take its place, the unequal heating of the earth's surface, by causing upward currents from the warmed portions, produces horizontal currents from the surrounding cooler regions inwards to the central ascending mass of heated air. The familiar land and sea breezes offer a good example of this action. Again, the density of the air lessens with increase of water-vapour. Hence moist air tends to rise as warmed air does, with a corresponding inflow of the drier and consequently heavier air from the surrounding tracts. Ascending moist air diminishes atmospheric pressure, as indicated by the fall of the barometer, and as it rises into higher regions of the atmosphere it expands, cools, and condenses into visible cloud and into showers that descend again to the earth.

Unequal and rapid heating of the air, or accumulation of aqueous vapour in the air, and possibly some other influences not yet properly

understood, give rise to extreme disturbances of pressure, and consequently to storms and hurricanes. For instance, the barometer sometimes indicates in tropical storms a fall of an inch and a half in an hour, showing that somewhere about a twentieth part of the whole mass of atmosphere has, in that short space of time, been displaced over a certain area of the earth's surface. No such sudden change can occur without the most destructive tempest or tornado. In Britain the tenth of an inch of barometric fall in an hour is regarded as a large amount, such as only accompanies great storms.[1] The rate of movement of the air depends on the difference of barometric pressure between the regions from and to which the wind blows. Since much of the potency of the air as a geological agent depends on its rate of motion, it is of interest to note the ascertained velocity and pressure of wind as expressed in the subjoined table:[2]—

| | Velocity in Miles per hour. | Pressure in Pounds per square foot. |
|---|---|---|
| Calm | 0 | 0 |
| Light breeze | 14 | 1 |
| Strong breeze | 42 | 9 |
| Strong gale | 70 | 25 |
| Hurricane[3] | 84 | 36 |

While the paramount importance of the atmosphere as the vehicle for the circulation of moisture over the globe, and consequently as powerfully influencing the distribution of climate and the growth of plants and animals, must be fully recognised by the geologist, he is specially called upon to consider the influence of the air in directly producing geological changes upon the surface of the land, and in augmenting the geological work done by water.

## § 1. Geological work of the Atmosphere on Land.

Viewed in a broad way, the air is engaged in the twofold task of promoting the disintegration of superficial rocks and in removing and re-distributing the finer detritus. These two operations, however, are so intimately bound up with each other that they cannot be adequately understood unless considered in their mutual relations.

**1. Destructive Action.**—Still dry air, not subject to much range of temperature, has probably little or no effect on minerals and rocks. The chemical action of the atmosphere takes place almost entirely through dissolved moisture. This subject is discussed in the section devoted to Rain. But sunlight produces remarkable changes on a few minerals. Some lose their colours (celestine, rose-quartz), others change it, as cerargyrite does from colourless to black, and realgar from red to orange-yellow. Some of these alterations may be explained by chemical modifications induced by such causes as the loss of organic matter and oxidation.

Effects of Lightning.—Hibbert has given an account of the

[1] Buchan's 'Meteorology,' p. 266.

[2] For another statement see Czerny, *Petermann's Mitt.* 1876, Ergänzungsheft.

[3] The velocity of the wind in gusts is sometimes as much as 150 miles an hour.

disruption by lightning of a solid mass of rock 105 feet long, 10 feet broad, and in some places more than 4 feet high, in Fetlar, one of the Shetland Islands, about the middle of the eighteenth century. The dislodged mass was in an instant torn from its bed and broken into three large and several lesser fragments. "One of these, 28 feet long, 17 feet broad, and 5 feet in thickness, was hurled across a high point of rock to a distance of 50 yards. Another broken mass, about 40 feet long, was thrown still farther, but in the same direction and quite into the sea. There were also many lesser fragments scattered up and down."[1] On 15th August 1901 a mass of grey gneiss, weighing about three and a half tons, was detached from the solid rock near Stockholm.[2]

The more usual effect of lightning, however, is to produce in loose sand or more compact rock patches of vitreous drops or bubbles coating the surface, also tubes termed *fulgurites*, which range up to 2½ inches in diameter. These tubes descend vertically, but sometimes obliquely, from the surface, occasionally branch, and rapidly lessen in dimensions till they disappear. They are formed by the actual fusion of the particles of the soil or rock surrounding the pathway of the electric spark. They have been most frequently found in loose sand. Abich has observed examples of such tubular perforations with vitreous walls in the porous reddish-white andesite at the summit of Little Ararat.[3] A piece of the rock about a foot long may be obtained perforated all over with irregular tubes having an average diameter of 3 centimetres. Each of these is lined with a blackish-green glass. As the whole summit of the mountain, owing to its frequent storms, is drilled in this manner, it is evident that the action of lightning may considerably modify the structure of the superficial portions of any mass of rock exposed on lofty eminences to frequent thunderstorms. Humboldt collected fulgurites from a trachyte peak in Mexico, and in two of his specimens the fused mass of the walls has actually overflowed from the tubes on the surrounding surface.[4]

[1] Hibbert's 'Shetland Islands,' p. 389, quoting from the MS. of Rev. George Low.

[2] G. Andersson, *Geol. Fören. Stockholm*, xxiii. (1901), p. 521; on splitting of rocks by lightning in North Wales, see J. R. Dakyns, *Geol. Mag.* 1900, p. 19.

[3] *Sitzb. Akad. Wiss. Wien*, lx. (1870), p. 155.

[4] G. Rose, *Zeitsch. Deutsch. Geol. Ges.* xxv. p. 112; Gümbel, *op. cit.* xxxiv. (1882), p. 647; A. Wichmann, *op. cit.* xxxv. (1883), p. 849. Fusion by lightning was observed by De Saussure in hornblende-schist on the summit of Mont Blanc (see also F. Rutley, *Q. J. G. S.* 1885, p. 152); by Ramond in mica-schist and limestone on a peak of the Pyrenees; by J. S. Diller on the basalt of Mount Thielson, Oregon, and on the top of Mount Shasta, California, *Amer. Journ. Sci.* Oct. 1884; by J. Eccles in glaucophane schist on Monte Viso, described by F. Rutley, *Q. J. G. S.* xlv. (1889), p. 60; by F. Rutley from Griqualand, *Min. Mag.* x. (1893), p. 280; by Miss E. Aston and Professor Bonney in serpentine from the summit of the Riffelhorn; by Professor W. Ramsay in green schist from the Hörnli near Zermatt, and in granite from the summit of Cir Mhor in the Isle of Arran, *Q. J. G. S.* lii. (1896), pp. 452, 456, 459. See also Professor Bonney, *Geol. Mag.* 1899, p. 1; W. Hallock, *Journ. Geol.* ix. (1901), p. 671, where a peculiar effect of lightning stroke is described traceable over an area 30 to 40 feet square, the rock being split into fragments and covered with white streaks due to incipient fusion. A. A. Julien, "A Study of the Structure of Fulgurites," *Journ. Geol.* ix. pp. 673-693.

**Effects of Changes of Temperature.**—Of far wider geological importance are the effects that arise among rocks and soils from the alternate expansion and contraction caused by daily or seasonal changes of temperature. In countries with a great annual range of temperature, considerable difficulty is sometimes experienced in selecting building-materials liable to be little affected by rapid or extreme variations in temperature, which induce an alternate expansion and contraction that prevents the joints of masonry from remaining close and tight.[1] If the daily thermometric variations are large, the effects are frequently striking. In Western America, where the climate is remarkably dry and clear, the thermometer often gives a range of more than 80° in the twenty-four hours. Thus in the Yellowstone district, at a height of 9000 feet above the sea, the author found the temperature of rocks exposed to the sun at noon to be more than 90° Fahr., and the thermometer at night to sink below 20°. In the Sahara and other African regions, as well as in Central Asia, the daily range is considerably greater. This rapid nocturnal contraction produces such a superficial strain as to disintegrate rocks into sand, or cause them to crack or peel off in skins or irregular pieces. Dr. Livingstone found in Africa (12° S. lat., 34° E. long.) that surfaces of rock which during the day were heated up to 137° Fahr., cooled so rapidly by radiation at night that, unable to sustain the strain of contraction, they split and threw off sharp angular fragments from a few ounces to 100 or 200 lb. in weight.[2] In the plateau region of North America, though the climate is too dry to afford much scope for the operation of frost, this daily vicissitude of temperature produces results that quite rival those usually associated with the work of frost. Among the Quitman mountains of Texas the bare rocks split with a loud report, the detached fragments varying in thickness from half an inch to four inches, and in superficial area from a few square inches to many feet.[3] By this continual operation cliffs are slowly disintegrated, the surface of arid plains is loosened, and the fine débris is blown away by the wind.

**Effects of Wind.**—The geological work directly due to the air itself is mainly performed by wind.[4] A dried surface of rock or soil, when

[1] In the United States, with an annual thermometric range of more than 90° Fahr., this difficulty led to some experiments on the amount of expansion and contraction in different kinds of building-stones, caused by variations of temperature. It was found that in fine-grained granite the rate of expansion was ·000004825 for every degree Fahr. of increment of heat; in white crystalline marble it was ·000005668; and in red sandstone ·000009532, or about twice as much as in granite. Totten, in *Silliman's Amer. Journ.* xxii. p. 136. See *ante*, pp. 392, 401.

[2] Livingstone's 'Zambesi,' pp. 492, 516. According to Stanley, cold rain falling on these sun-heated African rocks causes them to split open and peel off. *Proc. Roy. Geog. Soc.* xx. (1876), p. 142. N. S. Shaler, *Proc. Boston Soc. Nat. Hist.* xii. (1869), p. 292. See also J. Walther, *Bull. Soc. Imp. Natur. Moscow*, 1897, No. 3, p. 438, and his 'Gesetz der Wüstenbildung in Gegenwart und Vorzeit,' Berlin, 1900.

[3] H. von Streeruwitz, *4th Ann. Rep. Geol. Surv. Texas*, 1892, p. 144.

[4] The general geological effects of wind are discussed by F. Czerny, *Petermann's Mittheil.* Ergänzungsheft, No. 48. *Nature*, xv. p. 231. J. A. Udden, *Journ. Geol.* ii. (1894), pp. 318-331; and Appleton's *Pop. Sci. Monthly*, September 1896, p. 655.

exposed to wind, has the finer disintegrated particles blown away as dust or sand. The capacity of wind for this kind of transport depends mainly, on the one hand, upon the size, form and specific gravity of the materials to be moved, and on the other upon the velocity of the currents of air. Some experiments made by Mr. J. A. Udden in Illinois give an idea of this capacity and of the sifting power of the wind. The component grains of a coarse loam were separated by him into groups of different degrees of fineness and were then thrown into the air, when the wind was blowing at the rate of about eight miles in an hour. The following table gives the results :[1]—

| Average diameter of Particles. | Behaviour of the Particles when thrown into the air. |
|---|---|
| ·75 millimetre | Described a path diverging about 10° from a vertical line. |
| ·37 ,, | ,, ,, 45° ,, |
| ·18 ,, | ,, ,, but a few degrees from a horizontal line ; were blown upward by eddies. |
| ·08 ,, | Could scarcely be noticed to settle in transport. |
| ·04 ,, | Apparently completely borne up by the wind. |
| ·007 ,, | Completely borne up by the wind. |
| ·001 ,, | ,, ,, |

In gusts, however, and eddies caused by irregularities in the surface of the land, the velocity of the wind is such as to move much larger fragments of stone. Thus, on the exposed sea-cliffs of the Orkney and Shetland Islands it is common to find pieces of flagstone or slate weighing several pounds, which have been detached from the face of the precipice during gales and have been swept upwards and scattered over the heathy moor above. These fragments being thin and flat, expose larger surfaces to the wind than, bulk for bulk, are afforded by rocks that weather into rounded lumps, like granite and basalt.

When we consider the wide extent over which wind blows, it is not difficult to realise how potent its influence must be in the transport of material from one district to another. The process takes place familiarly before our eyes on every street and roadway, over cultivated ground, as well as on surfaces with which man has not interfered. It is geologically most marked in dry climates. Aridity indeed is its main cause. Mr. Flinders Petrie, the able Egyptian archæologist and explorer, has brought forward evidence of the abrading influence of the wind upon mud-brick walls and other buildings, and he estimates that in some parts of the Nile delta about eight feet of soil has been swept away by the wind during the last 2600 years, or nearly four inches in a century.[2] Many old fortifications in Northern China have been laid bare to the very foundations by the removal of the surrounding soil through long-continued action of wind.[3] In the dry plateaux of North America, too, though no human memorials serve there as measures, extensive denudation from the same cause is in progress.

It is not merely that the wind blows away what has already been loosened and pulverised. The grains of dust and sand are themselves

[1] *Journ. Geol.* ii. (1894), p. 323. [2] *Proc. Roy. Geograph. Soc.* 1889, p. 648.
[3] Richthofen's 'China,' Berlin, 1877, i. p. 97.

employed to rub down the surfaces over which they are driven. The nature and potency of the erosion done by sand-grains in rapid motion is well illustrated by the artificial sand-blast, in which a spray of fine siliceous sand, driven with great velocity, is made to etch or engrave glass.[1] The same process is sometimes seen at work in nature. Thus a large sheet of plate-glass, once a window in the lighthouse on Cape Cod, was so worn by the impact of sand-grains driven against it by the wind during a storm of not more than forty-eight hours' duration, that it was no longer transparent, and had to be removed; it is now in the National Museum, Washington.[2] The abrading and polishing effects of wind-blown sand have long been noticed on Egyptian monuments exposed to sand-drift from the Libyan desert.[3] Similar effects have been observed on dry volcanic plains of barren sand and ashes, as on the island of Volcano.[4] In some places it has been noticed that the stones exposed to the sand-drift are worn into facettes and have sharp edges.[5] On the sandy plains of Wyoming, Utah, and the adjacent territories, surfaces even of such hard materials as chalcedony are etched into furrows and wrinkles, acquiring at the same time a peculiar and characteristic glaze ("desert-polish"). There, also, large blocks of sandstone or limestone which have fallen from an adjacent cliff are attacked, chiefly at their base, by the stratum of drifting sand, until by degrees they seem to stand on narrow pedestals. As these supports are reduced in diameter the blocks eventually tumble over, and a new basal erosion leads to a renewal of the same stages of waste.[6] Hollows on rock-surfaces may also be noticed where grains of sand, or small pebbles kept in gyration by the wind,

[1] The student will find much valuable information on this subject in the experimental results obtained by Thoulet, *Comptes rend.* civ. p. 381; *Ann. des Mines*, xi. (1887), p. 199; and in the essay by Walther cited on p. 434.

[2] G. P. Merrill, *Journ. Geol.* iv. (1896), p. 714.

[3] An excellent account of the denudation phenomena of the Egyptian deserts will be found in an essay by J. Walther in vol. xvi. (1891) of the *Abhand. Königl. Sächsisch. Gesellsch. d. Wissensch.*, and in his volume already noticed, 'Gesetz der Wustenbildung in Gegenwart und Vorzeit.' The polishing of rocks by the sand of the Sahara is described by M. Choisy in his report, 'Documents relatifs à la Mission dirigée au Sud de l'Algérie,' 1890, p. 327.

[4] Kayser, *Z. Deutsch. Geol. Ges.* xxvii. p. 966.

[5] This form of sand-sculpture has been frequently discussed, and has been variously attributed to wind, ice, and river-erosion. See Prestwich, 'Geology,' i. p. 145; J. Walther, *Abh. K. Sachs. Ges. Wiss.* xvi. (1891), p. 445; J. H. Woodworth, *Amer. Journ. Sci.* xlvii. (1894), p. 63, where a bibliography of the subject will be found; Verworn, "Sandschliffe von Djebel Nakûs, ein Beitrag zur Entwickelungsgeschichte der Kantengerölle," *Neues Jahrb.* 1896, i. p. 200; E. Harlé, *Compt. rend. Geol. Soc. France*, 1900, p. 30; O. Abel, *Jahrb. K. K. Geol. Reichs*, 1902, p. 24. Steenstrup showed that the three-edged stones could not have been cut into their forms by river-action, *Geol. Fören. Stockholm*, x. p. 485, xiv. p. 493.

[6] See Gilbert in Wheeler's *Report of U. S. Geograph. Surv. W. of 100th Meridian*, iii. p. 82. W. P. Blake, *Union Pacific Railroad Report*, v. pp. 92, 230. *Amer. Journ. Sci.* xx. (1885), p. 178. Naumann, *Neues Jahrb.* 1874, p. 337. Cazalis de Fondouce, *Assoc. Française*, 1879, p. 646. Erosion by the wind in Saxon Switzerland is discussed by R. Beck, *Z. D. G. G.* xlvi. (1894), p. 537. Æolian action in New England is described by J. H. Woodworth in the paper referred to in the previous note. Many good illustrations are given by Walther in the essay above cited.

gradually erode the shallow cavities in which they lie. On a larger scale this action results in the scooping out of broad shallow basins, which when rain comes are turned into lakes. On the great plains of the United States such lakelets are abundant, having no outlets and no constant inlets, usually not permanent though sometimes lasting for years, and only disappearing after a succession of dry seasons. Their origin is to be ascribed to the action of wind on surfaces of shale bare of vegetation. The alternate filling and drying up of these basins keep their sites sterile, and the wind is thus aided in desiccating them and in sweeping the detritus that is produced on them by disintegration or is carried into them from the surrounding ground.[1]

As the result of the protracted action of wind upon an area exposed at once to great drought and to rapid vicissitudes of temperature, a continuous lowering of the general level takes place. The great sandy deserts thus produced represent, however, only a portion of the disintegration. Vast quantities of the finer dust are borne away by the wind into other regions, where, as will be immediately pointed out, they tend to raise the general level. Again, a considerable amount of fine dust and sand, blown into the neighbouring rivers, is carried down in their waters. In inland areas of drainage, indeed, like that of Central Asia, this transport does not finally remove the river-borne sediment from the basin of evaporation, but tends to fill up the lakes. Where, however, as in North America, rivers cross from the desert areas to the sea, there must be a permanent removal of wind-swept detritus by these streams. In the arid plateaux drained by the Colorado and its tributaries, so great has been the subaerial denudation that a thickness of thousands of feet of horizontal strata has been removed from the surface of level plains thousands of square miles in extent. This denudation, the extent of which is attested by the remaining cliffs and "buttes," or outliers, of the strata, appears to be in great measure due to the causes here discussed, augmented in some districts by the effects of occasional heavy storms of rain.

In regions where the temperature sinks to the freezing-point or below it, much transport of snow is effected by the wind. In polar latitudes, where snow falls not in flakes but in minute ice-needles, it remains dry and pulverulent; and as a snow-storm is often followed by a gale, the snow is swept off the frozen ground, which is then exposed to denudation alike by wind and by frost. A good deal of the fine dust of rocks is thus produced and removed. The hard ice-particles and the grains of stone wear down the surfaces of rock or frozen soil over which they are driven.[2]

One further effect produced by air in violent motion may be seen in the destruction caused by cyclones. Not only are houses demolished, with much damage to other property and loss of life, but permanent changes of more or less importance are produced upon the surface of a country. Loose rocks on the surface of cliffs are hurled down, and blocks of stone and loose gravel are swept away. Bnt the most obvious effects

[1] G. K. Gilbert, *Journ. Geol.* iii. (1895), p. 47.

[2] See an interesting paper by Dr. C. Davison, *Q. J. G. S.* l. (1894), p. 472, where numerous authorities on the subject of snowdrift are cited.

are those in wooded districts, where the trees are prostrated far and near in the path of the storm. On the 18th and 19th of May 1883, a succession of hurricanes passed over the States of Illinois and Wisconsin, with such fury that the brick chimney of a factory was carried to a distance of three-quarters of a mile, an entire house was lifted into the air and blown to pieces, and an oak two feet in diameter was dashed through a house. When such a storm passes over forest-ground in temperate latitudes, the surface-drainage may be so obstructed by the fallen stems, that marsh-plants spring up, and eventually the site of a forest may be occupied by a peat-moss (p. 607).

2. **Reproductive Action.**—Growth of Dust.—The fine dust and sand resulting from the general superficial disintegration of rocks would, if left undisturbed, accumulate *in situ* as a layer that would serve to protect the still undecayed portions underneath. Such a layer, indeed, partially remains, but, being liable to continual attack and removal, may be taken to represent, where it occurs, the excess of disintegration over removal. In the vast majority of cases, however, the superficial coating of loose material is not due merely to the direct action of the sun's rays and of the air, but in far greater degree to the work of rain, aided by the co-operation of plants and animals. To the layer thus variously produced, the name of Soil is given. Its formation is described at p. 459.

That wind plays an effective part in the re-distribution of superficial detritus is demonstrated by every cloud of dust blown from desiccated ground. We only need to take into account the multiplying power of time, to realise how extensively the soil of a district may be lowered, or, in other cases, may be replenished and heightened by the dust-storms of centuries. Dust and sand, intercepted by the leaves of plants, gradually descend into the soil, whither they are washed down by rain, so that even a permanently grassy surface may be slowly and imperceptibly heightened in this way, and a soil may be formed differing considerably in chemical composition from what would result merely from the decay of the subsoil.[1]

On the sites of ancient monuments and cities, this reproductive action of the atmosphere can be most impressively seen and most easily measured. In Europe, on sites still inhabited by an abundant population, the deep accumulations beneath which ancient ruins often lie are doubtless mainly to be assigned to the successive destructions and re-buildings of generation after generation of occupants. But at Nineveh, Babylon, and many other Eastern sites, mounds which have been practically untouched by man for many centuries consist of fine dust and sand gradually drifted by the wind round and over abandoned cities, and protected and augmented by the growth of vegetation.[2] In those arid lands, the air is

[1] C. Reid, *Geol. Mag.* 1884, p. 165.

[2] The rubbish which, in the course of many centuries, has accumulated above the foundations of the Assyrian buildings at Kouyunjik was found by Layard to be in some places twenty feet deep. It consisted partly of ruins, but mostly of fine sand and dust blown from off the plains and mixed with decayed vegetable matter. Layard, 'Nineveh and its Remains,' 3rd edit. ii. p. 120. See also Richthofen's 'China,' i. p. 97.

often laden with fine detritus, which drifts like snow round conspicuous objects and tends to bury them up in a dust-drift. In Central Asia, even when there is no wind, the air is often thick with fine dust, and a yellow sediment settles from it over everything. In Khotan an exceedingly fine dust sometimes so obscures the sun that even at midday one cannot read large print without a lamp. This dust, deposited on the soil, heightens and fertilises it, and is regarded by the inhabitants as a kind of manure, without which the ground would be barren.[1]

Loess.—This name has been given to a remarkable deposit, first described in the valley of the Rhine, but which has been found to cover vast areas both in the Old World and the New.[2] It is usually a yellowish homogeneous clay or loam, unstratified, and presenting a singular uniformity of composition and structure. When carefully examined, its quartz-grains are found to be remarkably angular, and its mica-flakes, instead of being deposited horizontally, as they are by water, occur dispersedly in every possible position and with no definite order.[3] The chief constituent of loess is always hydrated silicate of alumina, in which the scattered grains of quartz and flakes of mica are distributed. The deposit is somewhat calcareous, the lime being here and there segregated into curious concretionary forms (Lössmänchen, Lösspuppen, p. 439) by the action of infiltrating water. Though a firm unstratified mass, it is traversed by innumerable tubes, formed by the descent of roots and mostly crusted with carbonate of lime. These have generally a vertical position, and ramify downwards. Where the surface is covered with vegetation, they may be seen occupied by rootlets to a depth of a foot or a few feet from the surface. By means of these pipes a tendency is given to a vertical jointing of the mass. With these characters, the loess unites a remarkable peculiarity in respect of its organic remains, which consist chiefly of land-shells, sometimes in immense numbers, likewise of the bones of various herbivorous and carnivorous mammals, which are either identical with or closely allied to living species that abound on steppes and grassy plains. Freshwater shells are usually rare, and marine forms do not occur. Loess is found at all elevations, up to 5000 feet among the Carpathians, 8000 feet in Shansi, China, and probably to still higher altitudes farther west. In hilly regions it fills up the valleys, shading off on either side up the slopes into the angular débris of the adjoining rock. Elsewhere, it spreads over the surface so as completely to conceal the original inequalities of the ground. In Northern China, Richthofen found it to have a thickness of 1500 or possibly over 2000 feet, and to be cut into deep valleys and precipitous ravines, with cliffs 500 feet high, which are excavated into tiers of chambers and passages by a teeming population.[4]

[1] Johnson's "Journey to Hohi, the capital of Khotan," *Journ. Geog. Soc.* xxxvii. 1867, p. 1. H. B. Guppy, *Nature*, xxiv. (1881), p. 126.

[2] The calcareous clays of the arid regions of North America have been largely used for the manufacture of sun-dried bricks called in Spanish "adobe,"—a term which has been proposed as a geological designation for these deposits. I. C. Russell, *Geol. Mag.* 1889, p. 291.

[3] See Mr. Russell's paper cited in the previous note, p. 294.

[4] See Richthofen's description, *Geol. Mag.* 1882, p. 293, and his 'China,' above cited.

In the arid tracts of North America the loess or "adobe" is estimated to be sometimes 2000 or 3000 feet thick.[1]

Various theories have been proposed in explanation of this singular deposit. By some it has been referred to the operation of the sea; by others to the work of lakes or of rivers. But its wide extent, its independence of the altitude or contours of the ground, its uniform and unstratified character, the unworn condition of its component particles, and the nature of its organic remains, show that it cannot be assigned to the action of large bodies of water. Richthofen propounded in 1870 the opinion that the loess is mainly due to the long-continued drifting and deposit of fine dust by wind over areas more or less covered with grassy vegetation, aided by the washing influence of rain; and this view has been widely accepted. More recently Dr. C. Davison has suggested that the loess is best explained on the supposition that it has resulted from snowdrift.[2] Where rain is distributed somewhat equally throughout the year, little dust is formed; but where dry and wet seasons alternate, as in Central Asia, vast quantities of dust may be moved during the months of dry weather. When the dust falls on bare ground, it is eventually swept away by the wind; but where it settles down on ground covered with vegetation, it is in great measure protected from further transport, and thus heightens the soil.[3]

For atmospheric accumulations of this nature, Trautschold proposed the name *eluvium*. They originate *in situ*, or at least only by wind-drift, whereas *alluvium* requires the operation of water, and consists of materials brought from a greater or less distance.[4] For wind-formed deposits the term "æolian" is now commonly used.

Sandhills or Dunes.[5]—Winds blowing continuously upon sand

[1] Russell, *Geol. Mag.* 1889, p. 292.

[2] In the paper cited *ante*, p. 437.

[3] Richthofen, *Geol. Mag.* 1882, p. 297. For some of the more important contributions to this subject, see Richthofen's 'China,' vols. i. and ii.; also *Verh. Geol. Reichs.* 1878, p. 289; E. Tietze, *Verh. Geol. Reichs.* 1878, p. 113; 1881, p. 37; *Jahrb. Geol. Reichs.* 1881, p. 80; 1882, p. 11; 1883, p. 279; R. Pumpelly, *Amer. Journ. Sci.* xvii. (1879); E. W. Hilgard, *op. cit.* xviii. (1879), pp. 106, 427; I. C. Russell, *Geol. Mag.* 1899, pp. 288, 342; J. A. Udden, *Bull. Geol. Soc. Am.* ix. (1897), p. 6; F. Wahnschaffe, *Z. Deutsch. Geol. Ges.* 1886; *Jahrb. Preuss. Landesanst.* 1889, p. 328; A Sauer, *Zeitsch. für Naturwissensch.* lxii. (1889); T. W. Kingsmill, *Nature*, xlvii. (1892), p. 30; Kingsmill and Skertchly, *Q. J. G. S.* li. (1895), p. 238; Chamberlin, *Journ. Geol.* v. (1897), p. 795; C. R. Keyes, *Amer. Journ. Sci.* vi. (1898), p. 299; A. Viglino, *Boll. Soc. Geol. Ital.* xx. (1901), p. 311; and *postea*, Book VI. Part V. Sect. i. On the loess of Alsace, see E. Schumacher, *Commiss. Landesuntersuch. Elsass-Lothringen*, vol. ii. part i. (1889), p. 79; of South Russia, W. F. Hume, *Geol. Mag.* 1892, p. 540; of the Pampas, S. Roth, *Z. D. G. G.* xl. (1888), p. 422; O. Nordenskjöld, *Geol. Fören. Stockholm*, xxii. (1901), pp. 191-206, where the "Pampas-formation" is described.

[4] *Z. D. G. G.* xxxi. p. 578.

[5] For accounts of maritime sand-dunes, their extent, progress, structure, and the means employed to arrest their progress, the student may consult Andersen's 'Klitformationen,' 8vo, Copenhagen, 1861; Laval in *Annales des Ponts-et-Chaussées*, 1847, 2me sem.; Marsh's 'Man and Nature,' 1864, and the works cited by him; Forchhammer, *Edin. New Phil. Journ.* xxxi. (1841), p. 61; Élie de Beaumont, 'Leçons de Géologie pratique,'

drive it onward, and pile it into irregular heaps and ridges, called "dunes." This takes place more especially on windward coasts, either of the sea or of large inland lakes, where sandy shores are exposed to the drying influence of solar heat and wind; but similar effects may be seen even in the heart of a continent, as in the sandy deserts of the Sahara, Arabia, and in the arid lands of Utah, Arizona, &c. The dunes travel in parallel, irregular and often confluent ridges, their general direction being transverse to the prevalent course of the wind. Local wind-eddies cause many irregularities of form. In humid climates, rain-water or the drainage of small brooks is sometimes arrested between the ridges to form pools (*étangs* of the French coasts), where formations of peat occasionally take place. On the coast of Gascony, the sea for 100 miles is so barred by sand-dunes that in all that distance only two outlets exist for the discharge of the drainage of the interior. As fast as one ridge is driven away from a beach another forms in its place, so that a series of huge sandy billows, as it were, is continually on the move from the sea-margin towards the interior. A stream or river may temporarily arrest their progress, but eventually they push the obstacle aside or in front of them. In this way the river Adour, on the west coast of France, has had its mouth shifted two or three miles. Occasionally, as at the mouths of estuaries, the sand is blown across, so as gradually to exclude the sea, and thus to aid the fluviatile deposits in adding to the breadth of the land. In Fig. 90 a stream (*e e*) is represented as crossing a plain (*a*) at the margin of the sea or of a large inland sheet of water, bounded by a range of sand-dunes (*b b*) extending between the two lines of cliff (*c g*). The stream has been turned to its right bank by the advance of the dunes driven by a prevalent wind blowing in the direction of the arrows. A brook (*f*) has been arrested among the sandy wastes, whence,

Fig. 90.—Sand-dunes affecting land-drainage (*B.*).

i. p. 183; Winkler, *Cong. Internat. Géol.* 1878, p. 181. Information regarding the sands of the interior of continents will be found in Palgrave's 'Travels in Arabia'; Tristram, 'The Great Sahara,' 1860; Desor, "Le Sahara, ses différents types de déserts," *Bull. Soc. Sci. Nat. Neufchâtel*, 1864; A. Parran, *B. S. G. F.* xviii. (1890), p. 245; A. Choisy, 'Documents relatifs à la Mission dirigée au Sud de l'Algérie,' 1890, p. 323; Captain H. G. Lyons on the Libyan Desert, *Q. J. G. S.* (1894), p. 531; liii. (1897), p. 360; E. Fuchs, *Petermann's Mittheil.* 1879; A. Pomel, *Assoc. Française*, 1877, p. 428; G. Rolland, *B. S. G. F.*, 3me sér. x. p. 30, *La Nature*, 1882, *Soc. de Géog.* 1890; Richthofen's 'China,' i.; J. Walther's monograph on Deserts cited *ante*, p. 434; Sven Hedin on the deserts of Central Asia, *Peterm. Mitth.* Ergänzungsheft, No. 131 (1900); I. C. Russell on the subaerial deposits of North America, *Geol. Mag.* 1889, p. 289; Blake, in *Union Pacific Railroad Report*, vol. v.

after forming a few pools, it finds egress by soaking through the sandy barrier.

The nature of the grains of sand depends on the character of the rocks from the destruction of which they are derived, and their form and size are largely regulated by the force of the wind and the relative share taken by subaerial and subaqueous action in their production. Quartz is the most frequent constituent, but the other minerals of rocks also occur, especially those which are most capable of resisting mechanical trituration. In some cases, organic remains, such as particles of shells, nullipores, &c., form the main mass of the sand (pp. 443, 444).[1] The sand-grains liberated by inland subaerial disintegration are apt to be more angular than those brought within the influence of the wind along a shore-line.[2]

Perfect "ripple-marks" (p. 642) may often be observed on blown sand. The sand-grains, pushed along by the wind, travel up the long slopes and fall over the steep slopes. Not only do the particles travel, but the ridges also more slowly follow each other, as in Fig. 91.[3]

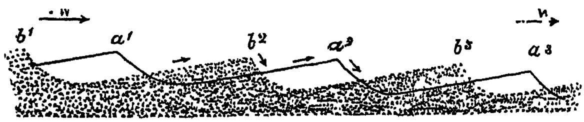



Fig. 91.—Diagram of Ripples in blown Sand. The ridges $b^1$, $b^2$, $b^3$, impelled in the direction of the arrows, W W, successively come to occupy the hollows $a^1$, $a^2$, $a^3$ (*B.*).

The western sea-board of Europe, exposed to prevalent westerly and south-westerly winds, affords many instructive examples of these æolian or wind-formed deposits. The coast of Norfolk is in some parts fringed with sand-hills 50 to 60 feet high. On parts of the coast of Cornwall,[4] the sand consists mainly of fragments of shells and corallines, and, through the action of rain upon these calcareous particles, becomes sometimes cemented by carbonate of lime (or oxide of iron) into a stone so compact as to be fit for building purposes. Long tracts of blown sand are likewise found on the Scottish and Irish[5] coast-lines. Sand-dunes extend for many leagues along the French coast, and thence, by Flanders and Holland, round to the shores of Courland and Pomerania. On the coast of Holland they are sometimes, though rarely, 260 feet high —a common average height being 50 to 60 feet.[6]

[1] Mr. Russell (*Geol. Mag.* 1889) refers to some parts of the sands of the arid lands of North America as being composed mainly of the cases of cyprids, blown away from the beds of dried-up lakes.

[2] Engravings of some of the sand-grains from the Egyptian deserts are given by Walther in the essay already cited.

[3] On the origin of ripple-mark, so frequent among sandstones, see p. 642.

[4] Ussher, *Geol. Mag.* (2), vi. p. 307, and authorities there cited. The upper parts of the blown sand are sometimes crowded with land-shells, the decay of which furnishes the cementing material (see Fig. 76).

[5] See Kinahan, *Geol. Mag.* viii. p. 155.

[6] On the growth of Holland through the operation of the wind and the sea, see Élie de Beaumont, 'Leçons de Géologie pratique,' i. A detailed description of the dunes of Holland is given by J. Lorié, *Arch. Musée Teyler*, sér. ii. vol. iii. part v. (1890), p. 375. A series of inland dunes in the south-west of Mecklenburg-Schwerin, between Neustadt, Lenzen and Boizenburg, is described by P. Sabban, *Mitth. Grossherz. Mecklenb. Geol.*

The breadth of this maritime belt of sand varies considerably. On the east coast of Scotland it ranges from a few yards to 3 miles; on the opposite side of the North Sea it attains on the Dutch coast sometimes to as much as 5 miles. The rate of progress of the dunes towards the interior depends upon the wind, the direction of the coast, and the nature of the ground over which they have to move. On the low and exposed shores of the Bay of Biscay, when not fixed by vegetation, they travel inland at a rate of about 16½ feet per annum, in Denmark at from 3 to 24 feet. In the course of their march they envelop houses and fields; even whole parishes and districts once populous have been overwhelmed by them.[1]

Along the margins of large lakes and inland seas many of the phenomena of an exposed sea-coast are repeated on a scarcely inferior scale. Among these must be included sand-dunes, such as those which, reaching heights of 100 to 200 feet on the south-eastern shores of Lake Michigan, have entombed forests, the tops of the trees being still visible above the drifting sand. Large dunes occur also on the eastern borders of the Caspian Sea, where the sand spreads over the desert region between that sea and the Sea of Aral, into which latter sheet of water the spread of the sand has driven the course of the Oxus, once a tributary of the Caspian.

In the interior of continents, the existence of vast arid wastes of loose sand, situated far inland and remote from any sheet of fresh water, suggests curious problems in physical geography. In some instances, these tracts have been at a comparatively recent geological period covered by the sea. Yet the disintegration of rock in torrid and rainless regions is so great (*ante*, p. 434), that the existing sand is doubtless mainly, if not entirely, of subaerial origin. The sandy deserts of the high plateaux of Western North America, which have never been under the sea for a long series of geological ages, show, as we have already found (p. 437), the mode and progress of their formation from atmospheric disintegration alone. In Asia lie the vast deserts of Gobi, where in some places ancient cities have been buried under the sand.[2] In Rajputana, wide tracts of sandy desert present a succession of nearly parallel ridges or waves of sand, varying up to 180 feet from trough to crest, and presenting long gentle slopes towards south-west, whence the prevalent winds blow, but with north-eastern fronts as steep as the sand will lie.[3] To the east of the Red Sea stretch the great sand-wastes of Arabia; and to the west those of Libya. The sandy wastes of the Sahara have in recent years been partially explored, especially by French observers from the Algerian frontier. According to M. Rolland, the sand is entirely due to the action of the wind, and though there is a transport of sand and fine dust, the position of the large dunes, sometimes 70 metres in height, remains on the whole unchanged.[4] In the south-east of Europe, over the steppes of Southern Russia and the adjacent territories, wide areas of sandy desert occur. Captain Sturt found vast deserts of sand in the interior of Australia, with long bands of dunes 200 feet high, united at the base and stretching in straight lines as far as the eye could reach.

Some of the most remarkable æolian formations are in course of accumulation at Bermuda and other coral-islands.[5] The finer coral-sand, with remains of shells,

*Landesanst.* viii. 1897. The same essay contains a discussion of the mineralogical composition of diluvial and alluvial sands, and the methods of distinguishing them. For an account of the sand-dunes of Western Europe, see W. Topley, *Pop. Science Rev.* xiv. (1875), p. 133.

[1] This destruction has more recently been averted to a great extent by the planting of pine forests, the turpentine of which has become the source of a large revenue.

[2] For information regarding the Central Asiatic wastes, see the works cited on p. 441; also Tchihatchef, *Brit. Assoc.* 1882, p. 356; T. D. Forsyth, *Journ. Roy. Geog. Soc.* xlvii. (1878), p. 1.

[3] Major C. Strahan in 'Report of Survey of India,' 1882-83.

[4] G. Rolland and A. Parran, in the memoirs cited on p. 441.

[5] Nelson, *Q. J. Geol. Soc.* ix. p. 200. Wyville Thomson's 'Atlantic,' vol. i. A.

echinoderms, calcareous algæ, and other organisms, is driven by the wind into dunes, the surface of which by the action of rain-water soon becomes cemented into coherence, while by degrees the whole mass of calcareous débris is converted into a hard compact rock which rings under the hammer. The highest point of Bermuda is 245 feet above the sea, and the whole land up to that height is composed of these hardened calcareous æolian deposits. As the land has subsided, these rocks have sunk to some extent below sea-level, and are now cut by the waves into shore-cliffs, islets, reefs and stacks. On the coast, between the mouth of the Indus and the peninsula of India, masses of limestone have been formed by the blowing ashore of foraminifera, which have been rolled and polished by the wind and have accumulated in masses that can be quarried for building purposes.[1]

Dust-showers, Blood-rain.—Besides the universal transport and deposit of dust and sand already described, a phenomenon of a more aggravated nature is observed in tropical countries, where great droughts are succeeded by violent hurricanes. The dust or sand of deserts and of dried lakes or river-beds is then sometimes borne away into the upper regions of the atmosphere, where, meeting with strong aerial currents which may transport it for many hundreds of miles, it descends again to the surface, in the form of "red fog," "sea-dust," or "sirocco-dust."[2] This transported material, usually of a brick-dust or cinnamon colour, is occasionally so abundant as to darken the air and obscure the sun, and to cover the decks, sails, and rigging of vessels which may even be hundreds of miles from land. Rain falling through such a dust-cloud mixes with it, and descends, either on sea or land, as what is popularly called "blood-rain." Occasionally the dust is brought down to the surface of the ground by snow.

This phenomenon is frequent on the north-west of Africa, about the Cape Verd Islands, in the Mediterranean and over the bordering countries. A microscopic examination of this dust by Ehrenberg led him to the belief that it contains numerous diatoms of South American species; and he inferred that a dust-cloud must be swimming in the atmosphere, carried forward by continuous currents of air in the region of the trade-winds and anti-trades, but suffering partial and periodical deviations. But much of the dust seems to come from the sandy plains and desiccated pools of the north of Africa. Daubrée recognised in 1865 some of the Sahara sand which fell in the Canary Islands. On the coast of Italy, a film of sandy clay, identical with that from parts of the Libyan desert, is occasionally found on windows after rain. In the middle of last century an area of Northern Italy, estimated at about 200 square leagues, was covered with a layer of dust which in some places reached a depth of one inch. In 1846 the Sahara dust reached Lyons, and it is said to have been since detected as far as Boulogne-sur-Mer.[3] Should the

Agassiz, *Bull. Mus. Comp. Zool. Harvard*, xxvi. (1895), p. 221, where some good photographic views of the æolian deposits will be found. See also A. E. Verrill, *Am. Journ. Sci.* ix. (1900), p. 313, where a bibliography of the Bermudas is given. The æolian accumulations of the Florida Keys are noticed by A. Agassiz, *Bull. Mus. Comp. Zool. Harvard*, xxviii. (1896), p. 45; the æolian sandstones of Fernando de Noronha by J. C. Branner, *Am. Journ. Sci.* xxxix. (1890), p. 247.

[1] F. Chapman, *Q. J. G. S.* lvi. (1900), p. 584.

[2] For illustrations see J. Milne, *Nature*, xlvi. (1892), p. 128; lvii. (1898), p. 463.

[3] A remarkable example occurred in March 1901, when a vast amount of dust was carried from the desert south of Algeria across Europe into Russia. It is estimated that not less than 1,800,000 tons of fine sand and dust were then transported, two-thirds of which fell to the south of the Alps. See Professor Rücker, *Nature*, lxiii. (1901), p. 514; lxiv. p.

travelling dust encounter a cooler temperature, it may be brought to the ground by snow, as has happened in the north of Italy, and more notably in the east and south-east of Russia, where the snows are sometimes rendered dirty by the dust raised by winds on the Caspian steppes.[1] It is easy to see how widespread deposits of dust may arise, mingled with the soil of the land, and with the silt and sand of lakes, rivers, or the sea; and how the minuter organisms of tropical regions may thus come to be preserved in the same formations with the terrestrial or marine organisms of temperate latitudes.[2]

The transport of volcanic dust by wind, already referred to (p. 292), may be again cited here, as another example of the geological work of the atmosphere. Thus, from the Icelandic eruptions of 1874-75, vast showers of fine ashes not only fell on Iceland to a depth of six inches, destroying the pastures, but were borne over the sea and across Scandinavia to the east coast of Sweden.[3] The remarkable sunsets of Europe during the winter and spring of 1883-84 are ascribed to the diffusion of the fine dust from the great Krakatoa eruption of August 1883 (p. 293). Considerable deposits of volcanic material may thus be formed, in the course of time, even far remote from any active volcano.

Transportation of Plants and Animals.—Besides the transport of dust for distances of perhaps thousands of miles, wind may also transport living seeds or spores, which, finally reaching a congenial climate and soil, may survive and spread. We are yet, however, very ignorant as to the extent to which this cause has actually operated in the establishment of any given local flora. With regard to the minute forms of vegetable life, indeed, there can be no doubt as to the efficacy of the wind to transport them across vast distances on the surface of the globe. Upwards of 300 species of diatoms have been found in the deposits left by dust-showers. Among the millions of organisms thus transported it is hardly conceivable that some should not fall still alive into a fitting locality for their continued existence and the perpetuation of their species. Animal forms of life are likewise diffused through the agency of winds. Insects and birds are often met with at sea, many miles distant from the land from which they have been blown. Such organisms are in this way introduced into oceanic islands, as is well shown in the case of Bermuda. Hurricanes, by which large quantities of water are sucked up from lakes and rivers over which they pass, may also transport part of the fauna of these waters to other localities.

Efflorescence Products.—Among the formations due in large measure to atmospheric action must be included the saline efflorescences which form upon the ground in the dry interior basins of continents. The steppes of Southern Russia, and the plains round the Great Salt Lake of Utah, may be taken as illustrative examples. Water, rising by

30; S. Meunier, *Compt. rend.* cxxxii. (1901), p. 894; Klein, *Sitzb. Berlin Akad.* No. xxxi. (23rd May 1901), p. 612. G. Hellmann and W. Meinardus (*Abhandl. K. Preuss. Meteorol. Inst.* ii. No. 1. (1901)) have given a detailed account of this fall.

[1] Consult an interesting paper by C. von Camerlander on snow with dust which fell in Silesia, Moravia and Hungary in February 1888, *Jahrb. Geol. Reichsanst.* xxxviii. (1888), p. 281. See also C. Abbe, *United States Monthly Weather Review*, January 1895.

[2] See Humboldt on dust whirlwinds of Orinoco, 'Aspects of Nature'; also Maury, 'Phys. Geog. of Sea,' chap. vi.; Ehrenberg's 'Passat-Staub und Blut-Regen,' *Berlin Akad.* 1847. A. von Lasaulx on so-called "cosmic dust," *Tschermak's Mineral. Mittheil.* 1880, p. 517.

[3] Nordenskjöld, *Geol. Mag.* (2), iii. p. 292. F. Zirkel, *Neues Jahrb.* 1879, p. 399. G. vom Rath, *ibid.* p. 506; and *ante*, p. 295.

capillary attraction through the soil to the surface, is there evaporated, leaving behind a white crust, by which the upper portion of the soil is covered and permeated. The incrustations consist of sodium-chloride, sodium- and calcium-carbonates, calcium- sodium- and potassium-sulphates in various proportions, these being the salts present also in the salt lakes of the same regions (p. 525).[1]

## § 2. Influence of the Air on Water.

The results of the action of the air upon water will be more fitly noticed in the section devoted to Water. It will be enough to notice here—

1. Alteration of the Water-level.—Variations in atmospheric pressure give rise to considerable fluctuations of the surface of large inland sheets of water, and even of the water-level and discharge of springs.[2] Rapid and great diminution of atmospheric pressure may also cause a rise in the level of the sea and produce great destruction (p. 562).

Again, wind blowing freshly across a lake or narrow sea drives the water before it, and keeps it temporarily at a higher level on the farther or windward side. Where a strong wind blows for some time along the length of a long lake, the rise of water-level from this cause may allow the waves to do a good deal of destruction to earth-banks, or even to walls and buildings. In vast lakes like those of North America, the amount of waste thus caused is often considerable. In a tidal sea, such as that which surrounds Great Britain, and which sends abundant long arms into the land, a high tide and a gale are sometimes synchronous. This conjunction makes the high tide rise to a greater height than elsewhere in those bays or firths which look windward, occasionally causing considerable damage to property by the flooding of warehouses and stores, with even a sensible destruction of cliffs and sweeping away of loose materials. On the other hand, a wind from the opposite quarter coincident with an ebb tide, by driving the water out of an inlet, makes the water-level lower than it would otherwise be. In inland seas where tides are small or imperceptible, and on large fresh-water lakes (p. 522), considerable oscillations of water-level may arise from the action of the wind. At Naples, for example, a long-continued south-west wind raises the level of the water several inches. Great destruction is sometimes caused by the rise of sea-level during cyclones (p. 562).

2. Ocean Currents.—These are mainly dependent for their existence and direction on the circulation of the atmosphere. The in-streaming of air from cooler latitudes towards the equator causes a drift of the sea-water in the same direction. As, owing to the rotation of the earth, these aerial currents tend to take a more and more westerly trend in approaching the equator, they communicate this trend to the marine currents, which, likewise moving into regions with a greater velocity of

[1] On efflorescence of Great Salt Lake region, see *Exploration of 40th Parallel*, i. sect. v. Consult also E. Tietze, "Entstehung der Salzsteppen," *Jahrb. Geol. Reichsanst.* 1877; and H. le Chatelier on the salt-crusts of Algeria, *Comptes rend.* lxxxiv. p. 396.

[2] S. Günther, "Luftdruckschwankungen in ihrem Einflusse auf die festen und flüssigen Bestandtheile der Erdoberfläche," *Gerland's Beiträge Geophys.* ii. p. 71.

rotation than their own, are all the more impelled in the same westerly direction. Hence the dominant equatorial current which flows westward across the great ocean. Owing, however, to the position of the continents across its path, this great current cannot move uninterruptedly round the earth. It is split into branches which turn to right and left, and, bathing the shores of the land, carry some of the warmth of the tropics into more temperate latitudes. Return currents are thus generated from cooler latitudes towards the equator (p. 558).

3. Waves.—The impulse of the wind upon a surface of water throws that surface into pulsations which range in size from mere ripples to huge billows. Long-continued gales from the seaward upon an exposed coast indirectly effect much destruction, by the formidable battery of billows which they bring to bear upon the land (p. 567). Wave-action is likewise seen in a marked manner when wind blows strongly across a broad inland sheet of water, such as Lake Superior (p. 523).

## Section ii. Water.

Of all the terrestrial agents by which the surface of the earth is geologically modified, by far the most important is water. We have already seen, when following hypogene changes, how large a share is taken by water in the phenomena of volcanoes and in other subterranean processes. Returning to the surface of the earth and watching the operations of the atmosphere, we soon learn how important a part of these is sustained by the aqueous vapour that pervades the atmosphere.

The substance which we term water exists on the earth in three well-known forms—(1) gaseous, as invisible vapour; (2) liquid, as water; and (3) solid, as ice. The gaseous form has already been noticed as one of the characteristic ingredients of the atmosphere (p. 37). Vast quantities of vapour are continually rising from the surface of the seas, rivers, lakes, snow-fields, and glaciers of the world. This vapour remains invisible until the air containing it is cooled down below its dew-point, or point of saturation,—a result which follows upon the union or collision of two aerial currents of different temperatures, or the rise of the air into the upper cold regions of the atmosphere, where it is chilled by expansion, by radiation, or by contact with cold mountains. Condensation appears only to take place on free surfaces, and the formation of cloud and mist is explained by condensation upon the fine microscopic dust of which the atmosphere is full.[1] At first minute particles of water-vapour appear, which either remain in the liquid condition, or, if the temperature is sufficiently low, are frozen into ice. As these changes take place over considerable spaces of the sky, they give rise to the phenomena of clouds. Further condensation augments the size of the cloud-particles, and at last they fall to the surface of the earth, if still liquid, as rain; if solid, as snow or hail; and if partly solid and partly liquid, as sleet. As the vapour is largely raised from the ocean-surface, so in great measure it falls

[1] Coulier and Mascart, *Naturforscher*, 1875, p. 400. Aitken, *Proc. Roy. Soc. Edin.* 1880 and 1891.

back again directly into the ocean. A considerable proportion, however, descends upon the land, and it is this part of the condensed vapour which we have now to follow. Upon the higher elevations it falls as snow, and gathers there into snow-fields, which, by means of glaciers, send their drainage towards the valleys and plains. Elsewhere it falls chiefly as rain, some of which sinks underground to gush forth again in springs, while the rest pours down the slopes of the land, swelling the brooks and torrents which, fed both by springs and rains, gather into broader and yet broader rivers that bear the accumulated drainage of the land out to sea. Thence once more the vapour rises, condensing into clouds and rain to feed the innumerable water-channels by which the land is furrowed from mountain-top to seashore.[1]

In this vast system of circulation, ceaselessly renewed, there is not a drop of water that is not busy with its allotted task of changing the face of the earth. When the vapour ascends into the air, it is comparatively speaking chemically pure. But when, after being condensed into visible form, and working its way over or under the surface of the land, it once more enters the sea, it is no longer pure, but more or less loaded with material taken by it out of the air, rocks or soils through which it has travelled. Day by day the process is advancing. So far as we can tell, it has never ceased since the first shower of rain fell upon the earth. We may well believe, therefore, that it must have worked marvels upon the surface of our planet in past time, and that it may effect vast transformations in the future. As a foundation for such a belief let us now inquire what it can be proved to be doing at the present time.

## § 1. Rain.

Rain effects two kinds of changes upon the surface of the land. (1) It acts *chemically* upon soils and stones, and, sinking under ground, continues, as we shall find, a great series of similar reactions there. (2) It acts *mechanically*, by washing away loose materials, and thus powerfully affecting the contours of the land.

1. **Chemical Action.**—This depends mainly upon the nature and proportion of the substances abstracted by rain from the air in its descent to the earth. Rain absorbs a little air, which always contains carbonic acid as well as other ingredients, in addition to its nitrogen and oxygen (p. 37). Rain thus washes the air and takes impurities out of it, by means of which it is enabled to work many chemical changes that it could not accomplish were it to reach the ground as pure water.

Composition of Rain-water.—Numerous analyses of rain-water show that it contains in solution about 25 cubic centimetres of gases per litre.[2] An average proportional percentage is by measure—nitrogen,

[1] For estimates of the distribution of rain over the globe, see Murray, *Scottish Geol. Mag.* 1887; Supan, *Petermann. Mittheil.* Ergänzungsheft, No. 124, 1898.

[2] Baumert, *Ann. Chem. Pharm.* lxxxviii. p. 17. The proportion of carbonic acid found by Peligot was 2·4. See also Bunsen, *op. cit.* xciii. p. 20; Roth, 'Chem. Geol.' i. p. 44; Angus Smith, 'Air and Rain,' 1872, p. 225.

64·47; oxygen, 33·76; carbonic acid, 1·77. Carbonic acid being more soluble than the other gases, is contained in rain-water in proportions between 30 and 40 times greater than in the atmosphere. Oxygen, too, is more soluble than nitrogen. These differences acquire a considerable importance in the chemical operations of rain. Other substances are present in smaller quantities. In England there is an average of 3·95 parts of solid impurity in 100,000 parts of rain.[1] Nitric acid sometimes occurs in marked proportions: at Bâle it was found to reach a maximum of 13·6 parts in a million, with 20·1 parts of nitrate of ammonia.[2] Sulphuric acid likewise occurs, especially in the rain of towns and manufacturing districts.[3] Sulphates of the alkalies and alkaline earths have been detected in rain. But the most abundant salt is chloride of sodium, which appears in marked proportions on coasts, as well as in the rain of towns and industrial districts. Rain taken at the Land's End in Cornwall during a strong south-west wind was found to contain 2·180 of chlorine, or 3·591 parts of common salt, in every 10,000 of rain. The mean proportion of chlorine over England is about 0·022 in every 10,000 parts of rain; at Ootacamund 0·003 to 0·004.[4]

In washing the air, rain carries down also inorganic particles or motes floating there; likewise organic dust and living germs.[5] As the result of this process the soil comes to be not merely watered but fertilised by the rain. Angus Smith cites the experience of J. J. Pierre, who found by analysis that in the neighbourhood of Caen, in France, a hectare of land receives annually from the atmosphere by means of rain:[6]—

[1] *Rivers Pollution Commission, 6th Rep.* p. 29.

[2] On the influence of nitrification, see Muntz, *Compt. rend.* cx. (1890), p. 1370.

[3] The occurrence of sulphuric and nitric acids in the air, especially noticeable in large towns, leads to considerable corrosion of metallic surfaces, as well as of stone and lime. The mortar of walls may often be observed to be slowly swelling out and dropping off, owing to the conversion of the lime into sulphate. Great injury is likewise done, from a similar cause, to marble monuments in exposed graveyards. See Angus Smith, 'Air and Rain,' p. 444. A. G., *Proc. Roy. Soc. Edin.* 1879-80, p. 518.

[4] Angus Smith, 'Air and Rain.' *Rivers Pollution Commission, 6th Rep.* 1874, p. 425. During a westerly gale on the Atlantic coasts of Britain, when the sea is white with foam, the air, elsewhere clear, may be seen to be quite misty alongshore from the clouds of fine spray swept by the wind from the crests of the breakers. This salt-water dust is borne far inland. From the investigations carried on at the Agricultural Laboratory, Rothamsted, it appears that the average proportion of chlorine is 2·01 per million parts of rain, which in a rainfall of 31·65 inches is equal to a discharge of 24 lbs. of pure sodium chloride per acre. At Cirencester, where the rainfall is 33·31 inches, the proportion of chlorine is 3·25 per million, which is equivalent to 40·3 lbs. of sodium chloride per acre. R. Warington, *Journ. Chem. Soc.* 1887, p. 502.

[5] Among the inorganic contents of rain and snow, fine terrestrial dust and spherules of iron, probably in part of cosmic origin, have been specially noted. See authorities cited *ante*, p. 93; A. von Lasaulx and C. Abbe, as cited on p. 445. On the geological significance of cosmic materials that fall to the earth's surface, see A. E. Nordenskjöld, 'Studier och Forskningar Föranledda af mina Resor i Höga Norden,' Stockholm, 1883. The organic matter of rain is revealed by the putrid smell which long-kept rain-water gives out.

[6] Angus Smith, 'Air and Rain,' p. 233.

| | | |
|---|---|---|
| Chloride of sodium | 37·5 kilogrammes. | |
| ,, potassium | 8·2 | ,, |
| ,, magnesium | 2·5 | ,, |
| ,, calcium | 1·8 | ,, |
| Sulphate of soda | 8·4 | ,, |
| ,, potash | 8·0 | ,, |
| ,, lime | 6·2 | ,, |
| ,, magnesia | 5·9 | ,, |

Not only rain, but also dew and hoar-frost abstract impurities from the atmosphere. The analyses performed by the Rivers Pollution Commission show that dew and hoar-frost, condensing from the lower and more impure layers of the air, are even more contaminated than rain, as they contain on an average in England 4·87 parts of solid impurity in 100,000 parts, with 0·198 of ammonia.[1]

It is manifest that rain reaches the surface by no means chemically pure water, but having absorbed from the air various ingredients which enable it to accomplish a series of chemical changes in rocks and soils. So far as we know at present, the three ingredients which are chiefly effective in these operations are oxygen, carbonic acid and organic matter. As soon as it touches the earth, however, rain-water begins to absorb additional impurities, notably increasing its proportion of carbonic acid and of organic matter, from decomposing animals and plants. Among the organic products most efficacious in promoting the corrosion of minerals and rocks are the so-called ulmic or humous substances that form with alkalies and alkaline earths soluble compounds, which are eventually converted into carbonates.[2] Hence as rain-water, already armed with gases absorbed from the atmosphere, proceeds to take up these organic acids from the soil, it is endowed with considerable chemical activity even at the very beginning of its geological career.

Chemical and mineralogical changes due to Rain-water.—In previous pages, it was pointed out that all rocks and minerals are, in varying degrees, porous and permeable by water, that probably no known substance can, under all conditions, resist solution in water, and that the subsequent solvent power of water is greatly increased by the solutions which it effects and carries with it in its progress through rocks (pp. 410, 411). The chemical work done by rain may be conveniently considered under the five heads of Oxidation, Deoxidation, Solution, Formation of Carbonates, and Hydration.

1. *Oxidation.*—The prominence of oxygen in rain-water, and its readiness to unite with any substance that can contain more of it, render oxidation a marked feature of the passage of rain over rocks. A thin oxidised pellicle is formed on the surface, and this, if not at once washed off, is thickened from inside until a crust is formed over the stone, while at the same time the common dark green or black colour of the original rock changes into a yellowish, brownish, or reddish hue. This process

[1] *Rivers Pollution Commission, 6th Rep.* p. 32.

[2] Senft, *Z. Deutsch. Geol. Ges.* xxiii. p. 665, xxvi. p. 954. This subject has been well treated in a paper by A. A. Julien, "On the Geological Action of the Humus Acids" (*Proc. Amer. Assoc.* xxviii. 1879, p. 311), to which further reference is made in later pages.

is simply a rusting of those ingredients which, like metallic iron, have no oxygen, or have not their full complement of it. The ferrous and manganous oxides so frequently found as constituents of minerals are specially liable to this change. In hornblende and augite, for example, one cause of weathering is the absorption of oxygen by the iron and the hydration of the resultant peroxide. Hence the yellow and brown sand into which rocks abounding in these minerals are apt to weather. Sulphides of the metals give rise to sulphates, and sometimes to the liberation of free sulphuric acid. Iron disulphide, for example, becomes copperas, which on oxidation of the iron gives a precipitate of limonite, with the escape of free sulphuric acid.[1]

2. *Deoxidation.*—Rain becomes a reducing agent by absorbing from the atmosphere and soil organic matter which, having an affinity for oxygen, decomposes peroxides and reduces them to protoxides. This change is especially noticeable among iron-oxides, as in the familiar white spots and veinings so common among red sandstones. These rocks are stained red by ferric oxide (hæmatite), which, reduced by decaying organic matter to ferrous oxide, is usually removed in solution as an organic salt or a carbonate. When the deoxidation takes place round a fragment of plant or animal, it usually extends as a circular spot; where water containing the organic matter permeates along a joint or other divisional plane, the decoloration follows that line. Another common effect of the presence of organic matter is the reduction of sulphates to the state of sulphides. Gypsum is thus decomposed into sulphide of calcium, which in water readily gives calcium carbonate and sulphuretted hydrogen, and the latter by oxidation leaves a deposit of sulphur. Hence from original beds of gypsum, layers of limestone and sulphur have been formed, as in Sicily and elsewhere (p. 93).[2]

3. *Solution.*—A few minerals (halite, for example) are readily soluble in water without chemical change, and without the aid of any intermediate element; hence the copious brine-springs of salt regions. In the great majority of cases, however, solution is effected through the medium of carbonic acid or other reagent. Limestone is soluble to the extent of about 1 part in 1000 of water saturated with carbonic acid. The solution and removal of lime from the mortar of a bridge or vault, and the deposit of the material so removed in stalactites and stalagmites (pp. 191, 475), likewise the rapid effacement of marble epitaphs in our churchyards, are instances of this solution. It has been shown that in the atmosphere of a large town, with abundant coal-smoke and rain, exposed inscriptions on marble become illegible in half a century. Pfaff determined that a slab of Solenhofen limestone, 2520 square millimetres in superficies, lost in two years, by the solvent action of rain, 0·180 gramme in weight, in three years 0·548, the original polish being replaced by a dull earthy surface on which fine cracks and incipient exfoliation began to appear. Taking the specific gravity of the stone at

[1] The decomposition of iron-pyrites has been the subject of detailed study by A. A. Julien, *Ann. New York Acad. Sci.* vol. iii. pp. 365-404; iv. pp. 125-224.

[2] The reducing action of organic acids is further described in Section iii. p. 598.

2·6, the yearly loss of surface amounts to $\frac{1}{72\cdot 8}$ millimetre, so that a crag of such limestone would be lowered 1 metre in 72,800 years by the solvent action of rain.[1] J. G. Goodchild, from observations of dressed surfaces of Carboniferous limestone in the north of England, has inferred that these surfaces have been lowered at rates varying from one inch in 240 years to the same amount in 500 years.[2] Dolomite is much more feebly soluble than limestone. As rain-water attacks the carbonate of lime more readily than the carbonate of magnesia, the rock is apt to acquire a somewhat porous or carious texture, with a corresponding increase in the proportion of its magnesian carbonate. Eventually the latter carbonate is dissolved and re-deposited in the pores of the rock, which then assumes a characteristic crystalline aspect. Among the sulphates, gypsum is the most important example of solution. It is dissolved in the proportion of about 1 part in 400 parts of water. Even silica is abstracted from rocks by natural waters.[3]

4. *Formation of Carbonates.*—Silicates of lime, potash, and soda, with the ferrous and manganous silicates which exist so abundantly in rocks, are attacked by rain-water containing carbonic acid, with the formation of carbonates of these bases and the liberation of silica. The felspars are thus decomposed. Their crystals lose their lustre and colour, becoming dull and earthy on the outside, and the change advances inwards until the whole substance is converted into a soft pulverulent clay. In this decomposition the whole of the alkali, together with about two-thirds of the silica, is removed, leaving a hydrous aluminous silicate or kaolin behind. But the rapidity and completeness of the process vary greatly, especially in proportion to the abundance of carbonic acid. Where it advances with sufficient slowness, most of the silica, after the abstraction of the alkali, may be left behind. In the case of magnesian minerals (augite, hornblende, olivine, &c.) the silicates of magnesia and alumina, being less soluble, may remain as a dark brown or yellow clay, coloured by the oxidation of the iron, while the lime and alkalies are removed.[4] Evidence of the progress of these changes may be obtained even for some distance from the surface in many massive rocks. Diabase, basalt, diorite, and other crystalline rocks, which may appear to be quite fresh, will often reveal, by the effervescence produced when acid is dropped on their newly broken and seemingly undecomposed surfaces, that their silicates have been attacked by meteoric water and have been partially converted into carbonates.[5]

5. *Hydration.* — Some anhydrous minerals, when exposed to the

[1] Pfaff, *Z. Deutsch. Geol. Ges.* xxiv. p. 405; and 'Allgemeine Geologie als exacte Wissenschaft,' p. 317. Roth, 'Allgemeine und Chem. Geol.' i. p. 70. A. G., *Proc. Roy. Soc. Edin.* x. 1879-80, p. 518. [2] *Geol. Mag.* 1890, p. 466.

[3] On the solution of silica under atmospheric conditions, see C. W. Hayes, *Bull. Amer. Geol. Soc.* viii. (1897), pp. 213-220.

[4] Roth, *op. cit.* i. p. 112.

[5] R. Müller, investigating the corrosive influences of carbonated water upon minerals and rocks, has shown that even in seven weeks so much mineral matter is dissolved as to be capable of being quantitatively determined. *Tschermak's Mittheil.* 1897.

action of the atmosphere, absorb water (become hydrous), and may then be more prone to further change. Anhydrite becomes, by addition of water, gypsum, the change being accompanied by an increase of bulk to the extent of about 33 per cent. Local uplifts of the ground and crumpling or fracture of rocks may sometimes be caused by the hydration of subterranean beds of anhydrite (p. 400). Many substances on oxidising likewise become hydrous. The oxidation of ferrous oxide in damp air gives rise to hydrous ferric oxide, with its characteristic yellow and brown colours on weathered surfaces.

Weathering.—This term expresses the general result of all kinds of meteoric action upon the superficial parts of rocks. As these changes almost invariably lead to disintegration of the surface, the word weathering has come to be naturally associated in the mind with a loosened, crumbling condition of stone. But the influence of the atmospheric agents is not invariably to destroy the coherence of the integral particles of rocks. In some cases, stones harden on exposure. Certain sandy rocks, for example, like the "grey wethers" (p. 165), and scattered Tertiary blocks in the Ardennes, become under meteoric influence a kind of lustrous quartzite. In other cases there may be more complex molecular re-arrangements, such as those remarkable transformations to which Brewster first called attention in the case of artificial glass.[1] He showed that in thin films of decomposed glass, obtained from Nineveh and other ancient sites, concentric agate-like rings of devitrification are formed round isolated points, closely analogous to those above described as artificially produced by the action of heated alkaline waters (p. 411), and that groups of crystals or crystallites, "probably of silex," are developed from many independent points in the decomposing layer. Coloured films indicative of incipient decomposition have been observed on surfaces of glass exposed only to the air of the atmosphere for twenty or thirty years. Brilliantly iridescent films have been produced on the glass of windows exposed for not more than twenty years to the air and ammoniacal vapours of a stable.[2] That similar transformations take place in the natural silicates of rocks seems in the highest degree probable. They may form the earliest stages of the change to the usual opaque earthly decomposing crust, in which, of course, all trace of any structure developed in the preliminary weathering is lost.[3]

As the name denotes, weathering is dependent on meteorological conditions, and varies, even in the same rock, as these conditions change, but is likewise almost infinitely diversified according to the structure, texture and composition of the rocks on which it acts.[4] In humid and temperate climates, it is mainly due to the combined

[1] *Trans. Roy. Soc. Edin.* xxii. 607; xxiii. 193. See *ante*, p. 414.

[2] This fact was observed by my friend the late Mr. P. Dudgeon, of Cargen, in an ill-ventilated cow-house, and I have seen the plates of glass removed from the windows. The process of decay in glass has been treated of in great detail by Mr. James Fowler, *Trans. Soc. Antiquaries*, xlvi. (1879), pp. 65-162.

[3] Reference may be made here to the liquid inclusions already alluded to as developed in felspar during the decomposition of gneiss, *ante*, p. 145.

[4] Mr. G. P. Merrill has written ably on the subject of weathering. See his "Principles

influence of rain and sunshine. Saturated with rain-water, which dissolves more or less of any soluble constituents that may be present, and thereafter exposed to the desiccating and expanding influence of the warm rays of the sun, rock-surfaces are disintegrated, breaking up into angular fragments or crumbling into dust.[1] In high mountainous situations, as well as in lower regions where the temperature falls below the freezing-point in winter, weathering is in large measure caused by the action of frost (p. 531); in arid lands subject to great and rapid alternations of temperature, it may be mainly due to the strain of alternate expansion and contraction, and the mechanical action of the wind (p. 434 *et seq.*).

Mere hardness or softness forms no sure index to the comparative power of a rock to resist weathering. Many granites, for instance, weather to clay, deep into their mass, while much softer limestones retain smooth, hard surfaces. Nor is the depth of the weathered surface any better guide to the relative rapidity of waste. A tolerably pure limestone may weather with little or no crust, and yet may be continually losing an appreciable portion of its surface by solution, while an igneous rock, like a diorite or basalt, may be encased in a thick decomposed crust and weather with extreme slowness. In the former case, the substance of the rock being removed in solution, few or no insoluble portions are left to mark the progress of decay; while in the igneous rock, the removal of but a comparatively small proportion causes disintegration, and the remaining insoluble parts are found as an external crust. Impure limestone, however, yields a weathered crust of more or less insoluble particles. Hence, as we have already seen (p. 110), the relative purity of limestones may be roughly determined from their weathered surfaces, where, if they contain much sand, the grains will be seen projecting from the calcareous matrix; should they be very ferruginous, the yellow hydrous peroxide, or ochre, will be found as a powdery crust; or if they be fossiliferous, they will commonly present the fossils standing out in relief. An experienced fossil-collector will always carefully search weathered surfaces of limestone, for he often finds there, delicately picked out by the weather, minute and frail fossils, which are wholly invisible on the freshly broken stone. This difference arises from the crystalline calcite of the organic remains being less soluble than the more granular calcite in which these are imbedded. Limestones frequently assume a remarkable channelled rugose surface, with projecting knobs, ridges and pinnacles especially developed in high bare tracts of ground (Karrenfelder).[2] They are likewise perforated by many holes, tunnels and cavernous spaces, due to the solvent action of water (p. 477).

Rocks liable to little chemical change are best fitted to resist weathering, provided their particles have sufficient cohesion to withstand the mechanical processes of disintegration.[3] Siliceous sandstones offer excellent examples of this permanence. Consisting mainly of the durable mineral quartz, they are sometimes able so to withstand decay, that buildings made of them still retain, after the lapse of centuries, the chisel-

of Rock-Weathering," *Journ. Geol.* iv. (1896), pp. 704-724, 850-870, and his volume, 'A Treatise on Rocks, Rock-Weathering and Soils,' New York, 1897, pp. xx. 411. There is also a valuable paper by Mr. I. C. Russell on "Subaerial Decay of Rocks and Origin of the Red Colour of certain Formations," *B. U. S. G. S.* No. 52 (1889), with a good bibliography of the subject. Mr. R. S. Tarr has pointed out the proofs of the comparative rapidity of weathering and stream-erosion in Arctic latitudes, *Amer. Geol.* xix. (1897), p. 131.

[1] This result can be instructively imitated by boiling and drying shales in the manner described in Book V. Sect. vii. for the search for fossils.

[2] Heim, *Jahrb. Schweiz. Alpenclubs*, xii. (1878). R. Bell, *Bull. Geol. Soc. Amer.* vi. (1895), p. 297. On the rate of weathering of limestone, see J. G. Goodchild, *Geol. Mag.* 1875, p. 326; 1890, p. 463; A. G., *Proc. Roy. Soc. Edin.* x. (1880), p. 518.

[3] On weathering of building-stones, see Julien, *Trans. New York Acad. Sci.* Jan. 1883. W. Wallace, *Proc. Phil. Soc. Glas.* xiv. (1882-83), p. 22. Professor C. Lloyd Morgan, *Proc. Bristol Nat. Soc.* v. (1886-87), part ii.

marks of the builders. Many sandstones, however, contain argillaceous, calcareous or ferruginous concretions which weather more rapidly than the surrounding rock, and

Fig. 92.—Weathered Sandstone Cliffs showing irregular Honeycombing and Weathering along planes of stratification (*B.*).

cause it to assume a honeycombed surface; others are full of a diffused cement (clay, lime, iron) the decay of which makes the rock crumble down into sand. In sandstones, as indeed in most stratified rocks, there is a tendency towards more rapid weathering along the planes of stratification, so that the stratified structure is brought out very clearly on natural cliffs (Fig. 92). In many ferruginous sandstones and clay ironstones, successive yellow or brown zones or shells may be traced inward from the surface, frequently due to changes of the ferrous carbonate into limonite, the interior remaining still fresh. In many prismatic massive rocks (basalt, diorite, &c.), segments of the prisms weather into spheroids, in which successive weathered rings form crusts like the concentric coats of an onion (Figs. 93, 94). Where one of these rocks has been intruded as a dyke, it sometimes decomposes to a considerable depth into a mass of brown ferruginous balls in a surrounding sandy matrix—the whole having at first a resemblance to a conglomerate made of rolled and transported fragments (Fig. 94).

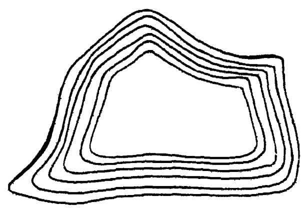


Fig. 93.—Rings of Weathering.

No rock presents greater variety of weathering than granite.[1] Some remarkably durable kinds only yield slowly at the edges of the joints, the separated masses gradually assuming the form of rounded blocks like water-worn boulders. Other kinds decompose to a depth of 50 feet or more, and can be dug out with a spade. In Cornwall and Devon, the kaolin from the rotted granite, largely extracted for pottery purposes, is found down to a depth of occasionally 600 feet. That what appears to be mere loose sand and clay is really rock decomposed *in situ*, is proved by the quartz-veins and bands of schorl-rock which ascend from the solid rock (*a*, Fig. 96) into the friable part (*b*), and by the entire agreement in structure between the two portions. Here and there, kernels of still undecomposed granite may be seen (as at *c c* in Fig. 97), surrounded by thoroughly decayed material, and, like the solid cores of basalt above-

[1] See a discussion of this subject by G. P. Merrill, *Bull. Geol. Soc. Amer.* vi. (1895), p. 321.

mentioned, presenting a deceptive resemblance to accumulations of transported materials. The granite boulders, so abundantly transported by the ice-sheets and glaciers of the

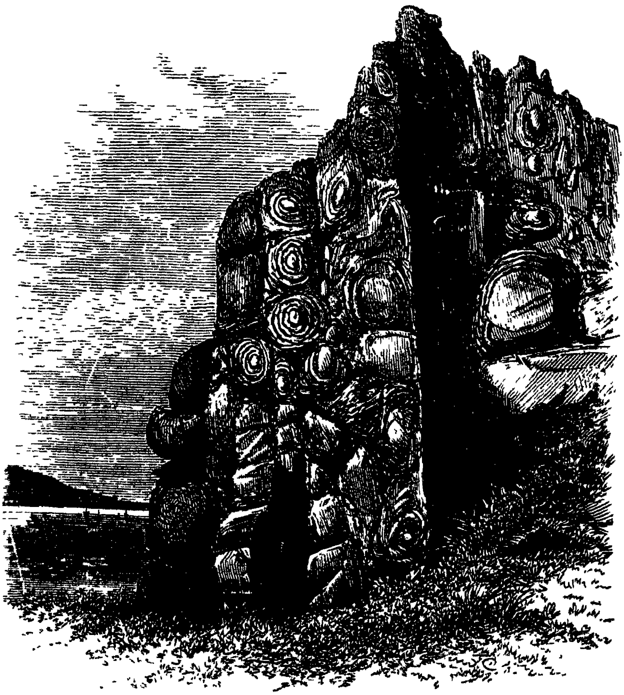


Fig. 94.—Spheroidal Weathering of Dolerite, North Queensferry.

Ice Age, no doubt generally originated in this way (Figs. 163, 164). Owing to its numerous joints, granite occasionally weathers into forms that resemble ruined walls. Large slabs, each defined by joint plains, weather out one above another like tiers of masonry (Fig. 98), until, loosened by disintegration, they slip off and expose lower parts of the rock to the same influences. Here and there, a separate block becomes so poised that it may be readily moved to and fro by the hand, as in the so-called "rocking-stones" of granite districts. As the disintegration varies with local differences in durability, some portions weather into cavities,[1] others into prominences, often with a singularly artificial appearance, as in the "rock basins" (Fig. 99) and "tors" (Fig. 98) of the south-west of England. The ruin-like weathering of dolomite gives rise in the Cevennes to some singularly picturesque scenery.

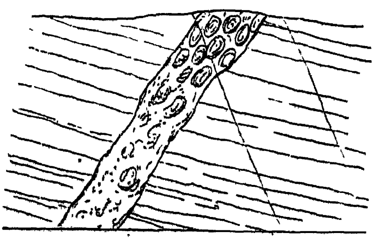


Fig. 95.—Felsite Dyke weathering into spheroids, Cornwall (*B.*).

To the influence of weathering, many of the most familiar minor contours of the

[1] An interesting case of the cavernous weathering of granite is described by P. Choffat, *Com. Dires. Trabal. Geol. Lisbon*, iii. (1895), p. 17.

land may be traced. So characteristic are these forms for particular kinds of rock, that they serve as a means of recognising them even from a distance. (Book VII.)

In countries which have not been under water for a vast lapse of time, and where consequently the superficial rocks have been continuously exposed to subaerial disintegration, thick accumulations of "rotted rock" are found on the surface. The

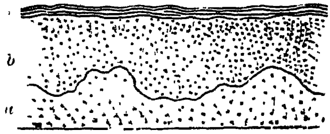



Fig. 96.—Decomposition of Granite. *a*, Solid granite; *b*, decomposed granite; *c*, vegetable soil.

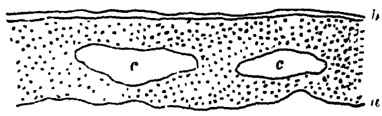



Fig. 97.—Decomposition of Granite. *a*, Solid granite; *b*, decomposed granite; *c*, *c*, kernels of still undecomposed granite.

extent of this change is sometimes impressively marked in areas of calcareous rocks. Limestone being mostly soluble, its surface is continually dissolved by rain, while the insoluble portions remain behind as a slowly increasing deposit. In regions which, possessing the necessary conditions of climate, have been for a long period unsubmerged, tracts of limestone, unprotected by glacial or other accumulations, are found to be

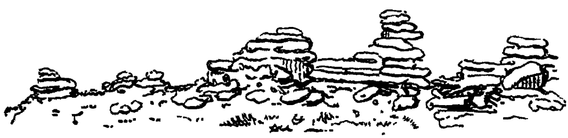


Fig. 98.—Weathering of Granite into "tors" along its joints (*B.*).

covered with a red loam or earth. This characteristic layer occurs on a limited scale over the chalk of the south-east of England, where, with its abundant flints, it lies as the undissolved ferruginous residue of the chalk that has been removed to a depth of many yards. It occurs likewise in swallow-holes and other passages dissolved out of calcareous masses, and forms the well-known red earth of bone caves. In south-eastern

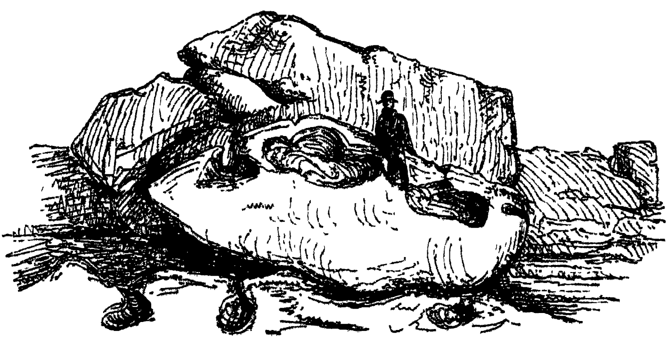


Fig. 99.—The "Kettle and Pans," St. Mary, Scilly; cavities weathered out of Granite (*B.*).

Europe it plays an important part among superficial deposits, being extensively developed over the limestone districts, especially in Istria and Dalmatia, where it is known as the ferruginous red earth or *terra rossa*.[1] It is seen also in the *Laterite* of

[1] On the origin of "Terra Rossa," see M. Neumayr, *Verhandl. Geol. Reichsanst.* 1875, p. 50; Th. Fuchs, *op. cit.* p. 194; E. von Mojsisovics, *Jahrb. Geol. Reichsanst.* xxx. (1880),

India,[1] in the red earth of Bermuda,[2] and in the red residual clays and earths of the southern Appalachian region of the United States.[3]

Other remarkable examples of similar subaerial waste have been specially noticed among crystalline schists and eruptive rocks. In Brazil, the crystalline rocks are said to be sometimes decayed to a depth of more than 300 feet.[4] In Massachusetts, Pennsylvania, and generally in the middle and southern Atlantic States of North America, the depth of disintegration appears gradually to increase southward from the limits where the country has been "glaciated" by ice-sheets during the Glacial period.[5] In Central Asia, a similar superficial decay has been observed.[6] Dr. Sterry Hunt has specially drawn attention to the geological importance of this prolonged disintegration *in situ*. Mr. Pumpelly points out that, as masses of decomposed rock may be observed to a depth of over 100 feet, the surface of the still solid rock underneath presents ridges and hollows, succeeding each other according to varying durability under the influence of percolating carbonated water. In this kind of weathering, where erosion does not come into play, it is evident that the resulting topography must, in some important respects, differ from that of an ordinary surface of superficial denudation. In particular, rock-basins may be gradually eaten out of the solid rock. These will remain full of the decomposed material, but any subsequent action, such as that of glacier-ice, which could scoop out the detritus, would leave the basins and their intervening ridges exposed.[7]

Rate of Weathering.—Careful measurements are much needed of the rate at which different kinds of rock under varying climatic conditions yield to the influences of the weather. Some particulars have been given above (p. 451) as to the progress of the solution of the surface of

p. 210; E. Tietze, *op. cit.* xxx. (1880), p. 729; Lorenz, *Verh. Geol. Reichs.* 1881, p. 81; C. de Georgi, *Boll. Com. Geol. Ital.* vii. p. 294. It is included among the ferruginous deposits by Stoppani ('Corso di Geologia,' iii. p. 534). See also W. Spring, *Neues Jahrb.* 1899, i. p. 47; I. C. Russell, *B. U. S. G. S.* No. 52 (1889), p. 44; J. Cornet, *Bull. Soc. Belg. Geol.* x. (1896), pp. 44-116. W. O. Crosby has discussed the contrast in colour of the soils in high and low latitudes, *Proc. Boston Soc. Nat. Hist.* xxiii. p. 219. Neumayr shows that the Terra Rossa is of various ages; in the Karst it encloses Miocene mammals.

1 'A Manual of the Geology of India,' by H. B. Medlicott and W. T. Blanford (1879), chap. xv.

2 'The Atlantic,' by Sir Wyville Thomson, p. 293.

3 I. C. Russell, *ut supra*.

4 Liais, 'Géologie du Brésil,' p. 2. *Ann. des Mines*, 7me sér. viii. p. 698. T. Belt, 'Naturalist in Nicaragua' (1874), p. 86. R. Pumpelly, *Bull. Soc. Geol. Amer.* ii. p. 210; J. C. Branner, *ibid.* vii. (1896), pp. 256, 295-300; O. A. Derby, *Journ. Geol.* (iv. (1896), pp. 529-540), throws doubt on the great depth of decay said to be general in Brazil. T. Sterry Hunt (*Amer. Journ. Sci.* 3rd ser. vii. p. 60; xxvi. (1883), p. 196; *Geol. Mag.* 1883, p. 310; *American Naturalist*, ix. (1875), p. 471) dwells especially on the great geological antiquity of the weathered crust. On the secular rock-weathering of the Swedish mountains, see Nathorst, *Geol. Fören. Stockholm Förhand.* 1879, iv. No. 13.

5 I. C. Russell, *supra cit.*; W. O. Crosby, *Proc. Nat. Hist. Sci. Boston*, xxiii. p. 219.

6 On a smaller scale it is also to be noted in the granite and killas (phyllite) of Cornwall and Devon, which, not having suffered from the abrading action of the ice of the Glacial period, show a deep cover of rotted rock, and afford some indication of what may have been elsewhere the condition of Britain before the period of glaciation. The sea-cliffs along the north coast of Cornwall expose instructive sections of the deep upper decomposed, and of the lower blue solid killas, with the remarkably uneven boundary along which they pass into each other.

7 Pumpelly, *Amer. Journ. Sci.* 3rd ser. xviii. 136; L. S. Burbank, *Proc. Bost. Nat. Hist. Soc.* xvi. (1874), part ii. p. 150; also *postea*, p. 552.

limestones, but we require detailed investigation of the net results of all the various atmospheric agencies upon faces of cliff and slope composed of all kinds of rock, both stratified and unstratified. Inquiries of this kind might well be organised on an international basis. They would furnish some more precise indications than are now available of the rate of the modern denudation of a land-surface, and would afford valuable data for estimates of the value of geological time. As an example of the kind of observations required, reference may be made to those undertaken by Prof. G. F. Wright, at the instance of the New York Central Railroad, with a view to ascertain the rate at which the lateral walls of the gorge of Niagara are now decaying under atmospheric influences. These walls consist of shales and limestones in nearly horizontal sheets, which are fully exposed to the air. It appears that since the railway was built in 1854, gradually descending along the face of the gorge, the shales have crumbled away in some places as much as 14 feet, and even 20 feet, in fifty-five years. The average rate of recession of these great cliffs is computed to be as much as an inch and a half annually. Hence in computing the age of the gorge as the result of river-erosion (p. 500), we must also take into account the subsequent widening of the defile by the continual decay and recession of the walls.[1]

Formation of Soil.—On level surfaces of rock the weathered crust may remain with comparatively little re-arrangement until plants take root on it, and by their decay supply organic matter to the decomposed layer, which eventually becomes what we term "vegetable soil." Animals also furnish a smaller proportion of organic ingredients. Though the character of soil depends primarily on the nature of the rock out of which it has been formed, its fertility largely arises from the commingling of decayed animal and vegetable matter with decomposed rock.

A gradation may be traced from the soil downwards into what is termed the "subsoil," and thence into the solid rock underneath (Fig. 100). Between soil and subsoil a marked difference in colour is often observable, the former being yellow or brown, when the latter is blue, grey, red, or other colour of the rock beneath.[2] This contrast, evidently due to oxidation and hydration, especially of the iron, extends downwards as far as the subsoil is opened up by rootlets and fibres to the ready descent of rain-water. The yellowing of the subsoil may even occasionally be noticed around some stray rootlet which has struck down farther than the rest, below the general lower limit of the soil (*postea*, p. 598).

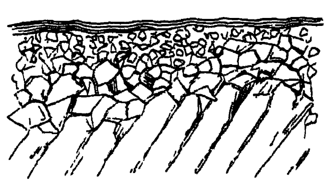


Fig. 100.—Section showing the upward passage of Rock (*a*) into Subsoil (*b*), and thence into Vegetable Soil (*c*).

[1] G. F. Wright, *Pop. Sci. Monthly*, June 1899; *American Geologist*, xxix. 1902, p. 140.

[2] Deceptive appearances of a break between the soil or subsoil and what lies beneath are sometimes produced by this means. See W. Whitaker, *Q. J. Geol. Soc.* xxxiii. p. 122; E. Van den Broeck, *Mém. Couronn. Acad. Brux.* 1881; J. Gosselet, 'Le Sol arable et le Sous-sol,' *Ann. Soc. Géol. Nord.* xxviii. (1899), p. 307.

Mr. Darwin observed many years ago that a layer of soil, three inches in depth, had grown above a layer of burnt marl spread over the land fifteen years previously; also that in another example, a similar layer had, as it were, sunk beneath the soil, to a depth of twelve or thirteen inches in eighty years. He connected these facts with the work of the common earth-worm, and concluded that the fine loam which had grown above these original superficial layers had been carried up to the surface, and had been voided there in the familiar form of worm-castings.[1] This action of the earth-worm is doubtless highly important, but, as Richthofen has pointed out, we have to take also into account the gradual augmentation of level due to the daily deposit of dust (*ante*, p. 438, and *postea*, p. 600).

Soil being composed mainly of inorganic, and to a slight extent of organic, materials, the proportion between these two elements is a question of high economic importance. With regard to the organic matter, it is the experience of practical agriculturists in Britain that oats and rye will grow upon a soil with 1½ per cent of organic matter, but that wheat requires from 4 to 8 per cent.[2] To a geologist, this organic matter has much interest, as the source of most of the carbonic acid with which so wide a series of changes is worked by subterranean water. The inorganic portion of soil, or still undissolved residue of the original surface-rock, varies from a loose, open substance with 90 per cent or more of sand, to a stiff, cold, retentive material with more than 90 per cent of clay. When this sand and clay are more equally mixed they form a "loam."[3]

Reference has just been made to the thick accumulation of rock decomposed *in situ* observable in certain regions which, having been above the sea for a lengthened period, have been long exposed to the action of weathering. Where this action has been supplemented by that of rain, widespread formations of loam and earth have been gathered together. These are well illustrated by the "brick-earth," "head," and "rain-wash" of the south of England—earthy deposits, with angular stones, derived from the subaerial waste of the rocks of the neighbourhood.[4]

[1] *Geol. Trans.* v. (1840), p. 505; and his more recent researches in his volume on 'Vegetable Mould.' See also C. Reid, *Geol. Mag.* 1884, p. 165.

[2] Johnston's 'Elements of Agricultural Chemistry,' p. 80.

[3] In the elaborate description of the soils of Russia by Professor Sibirtzew already cited (*ante*, p. 161), he classifies the soils of that region as follows: (1) lateritic; (2) dust-formed; (3) soils of the dry steppes or desert-steppes; (4) tchernozoms or black earths; (5) soils of the wooded steppes and of the regions where the trees shed their leaves; (6) grassy and "podzols"; (7) soils of the "tundras." For measurements of the permeability of soils, see Hondaille and Semichow, *Compt. rend.* cxv. (1892), p. 1015.

[4] Godwin-Austen, *Q. J. G. S.* vi. p. 94, vii. p. 121; Foster and Topley, *op. cit.* xxi. p. 446; Prestwich, *Q. J. G. S.* xlviii. (1892), p. 263. The vast extent of some superficial formations, like the "loess" above referred to (p. 439), has often suggested submergence below the sea. But when, instead of marine organisms, only terrestrial, fluviatile, or lacustrine remains occur in them, as in the brick-earths and loess, the idea of marine submergence cannot be entertained. The remarkable "tundras" or steppes of Siberia, and the

2. **Mechanical Action.**—Besides chemically corroding rocks and thereby loosening the cohesion of their particles, rain acts mechanically by washing off these particles, which are held in suspension in the little rain-runnels or are pushed by them along the surface. The amount and rapidity of this action do not depend merely on the annual quantity of rain. A comparatively large rainfall may be so equably distributed through a year or season as to produce less change than may be caused by a few heavy rain-storms which, though inferior in total amount of precipitated moisture, descend rapidly in great volume. Such copious rains as those of India, by deluging the surface of a country and rapidly flooding its water-courses, may transport in a few hours an enormous amount of sand and mud to lower levels.[1] Another feature to be kept in view is the angle of declivity: the same amount of rain will perform vastly more mechanical work if it can swiftly descend a steep slope, than if it has to move tardily over a gentle one.

Removal and Renewal of Soil.—Élie de Beaumont drew attention to what appeared to be proofs of the permanence or long duration of the layer of vegetable soil.[2] But the cases cited by him are not inconsistent with a belief that the doctrine of the persistence of the soil is true rather of the layer as a whole, than of its individual particles.[3] Were there no provision for its renewal, soil would comparatively soon be exhausted, and would cease to support the same vegetation. This result, indeed, occurs partially, especially on flat lands, but would be far more widespread were it not that rain, gradually washing off the upper part of the soil, exposes what lies beneath to further disintegration. This removal takes place even on grass-covered surfaces, through the agency of earthworms, by which fine particles of loam are brought up and exposed to the air, to be dried and blown away by wind, or washed down by rain. The lower limit of the layer of soil is thus made to travel downward into the subsoil, which in turn advances into the underlying rock. As Hutton long ago insisted, the superficial covering of soil is constantly, though slowly, travelling to the sea.[4] In this ceaseless transport, rain acts as the great carrying agent. The particles of rock and of soil are, step by step, moved downward over the face of the land, till they reach the nearest brook or river, whence their seaward progress may be rapid. A heavy rain discolours the water-courses of a country, because it loads them with the fine débris which it removes from the general surface of

"black earth" of Russia, are modern examples of such extensive formations, which are certainly not of marine origin, but point to long-continued emergence above the sea. (Murchison, Keyserling and De Verneuil's 'Geology of Russia.' Belt, *Q. J. G. S.* xxx. p. 490; also *postea*, p. 606.) More ancient illustrations are supplied by the vast subaerial and fresh-water formations of the interior of North America, and by those on the flanks of the Himalaya chain.

1 These rains sometimes fall at Chirapungi to the enormous amount of 40·8 inches in 24 hours (*Nature*, xlviii. (1893), p. 77). The quantity of soil and earth swept into the rivers and transported by them to the sea in so short a space of time is almost incredible.

2 'Leçons de Géologie pratique,' i. p. 140.

3 A. G., *Trans. Geol. Soc. Glasgow*, iii. p. 170.

4 'Theory of the Earth,' part ii. chaps. v. vi.

the land. In this way, rain serves as the means whereby the work of other disintegrating forces is made conducive to the general degradation of the land. The decomposed crust produced by weathering, which would otherwise accumulate over the solid rock, and in some measure protect it from decay, is removed by rain, and a fresh surface is thereby laid bare to further decomposition.

Movement of Soil-cap.—In some countries, where the ground is covered with a thick spongy mass of vegetation exposed to considerable variation of temperature and moisture, appearances have been observed of an extensive slipping of the layer of soil to lower levels, bearing with

Fig. 101.—Rain-eroded pillars of Old Red Conglomerate, Fochabers.

it whatever may be growing or lying upon it. Such are the so-called "stone-rivers" of the Falkland Islands, and the superficial débris of certain parts of the west coast of Patagonia.[1] In Western Europe, indications of a similar movement may often be noticed on the sides of hills or valleys. On the Canadian Pacific Railway the track of rails is in some places slowly shifting its position from this cause.

Unequal Erosive Action of Rain.—While the result of rain action is the general lowering of the level of the land, this process necessarily advances very unequally in different places. On flat ground, the waste may be quite inappreciable, except after long intervals and by the most accurate measurements, or it may even give place to deposition, the fine detritus washed off the slopes being spread out, so as actually to heighten the alluvial surface. In numerous localities, great variations in the rate

[1] Wyville Thomson's 'Atlantic,' ii. p. 245. R. W. Coppinger, *Q. J. Geol. Soc.* 1881, p. 348. See *postea*, under "Landslips," p. 480

of erosion by rain may be observed. Thus, from the pitted, channelled ground lying immediately under the drip of the eaves of a house, fragments of stone and gravel stand up prominently, because the earth around and above them has been washed away by the falling drops, and because, being hard, they resist the erosive action and screen the earth below them. On a larger scale the same kind of operation may be noticed in districts of conglomerate, where the larger blocks, serving as a protection to the rock underneath, come to form, as it were, the capitals of slowly deepening columns of rock (Fig. 101).

Fig. 102.—Earth-pillars left by the weathering of Moraine-stuff, Tyrol.

In certain valleys of the Alps a stony clay is cut by the rain into pillars, each of which is protected by, and indeed owes its existence to, a large block of stone which lay originally in the heart of the mass (Fig. 102). These columns, or "earth-pillars," are of all heights, according to the original positions of the stones. More colossal examples have been described by Hayden from the conglomerates of Colorado. Remarkable illustrations of the same results have been noted by Captain Dutton on the Zuñi Plateau, New Mexico, where large blocks from an escarpment of the hard Dakota sandstone have rolled down for a thousand feet, and have come to rest on softer calcareous sandstones which, being more easily wasted, have been carved into pillars each capped with one of the fallen blocks.[1]

There are instances, however, where the disintegration has been so complete that

[1] *6th Ann. Rep. U. S. G. S.* 1884-85, p. 154.

only a few scattered fragments remain of a once extensive stratum, and where it may not be easy to realise that these fragments are not transported boulders. In Dorsetshire and Wiltshire, for example, the surface of the country is in some parts so thickly strewn with fragments of sandstone and conglomerate "that a person may almost leap from one stone to another without touching the ground. The stones are frequently of considerable size, many being four or five yards across, and about four feet thick."[1] They are found lying abundantly on the Chalk, suggestive at first of some former agent of transport by which they were brought from a distance. They are now, however, generally admitted to be simply fragments of some of the sandy Tertiary strata which

Fig. 103.—Typical "Bad Lands" carved by subaerial denudation out of Tertiary strata, base of Scott's Bluff, Western Nebraska. Photograph by Mr. N. H. Darton, U.S. Geol. Survey.

once covered the districts where they occur. While the softer portions of these strata have been carried away, the harder parts (their hardness perhaps increasing by exposure) have remained behind as "grey wethers," and have subsequently suffered from the inevitable splitting and crumbling action of the weather. Similar blocks of quartzite and conglomerate, referable to the disintegration of Lower Tertiary beds *in situ*, are traceable in the north-east of France up into the Ardennes, showing that the Tertiary deposits of the Paris basin once had a much wider extension than they now possess.[2] On a far grander scale, the apparent caprice of general subaerial disintegration is

[1] They have been used for the huge blocks of which Stonehenge and other of the so-called Druidical circles have been constructed, hence they have been termed Druid Stones. Other names are Sarsen Stones (supposed to indicate that their accumulation has been popularly ascribed to the Saracens), and Grey Wethers, from their resemblance in the distance to flocks of (wether) sheep. See *Descriptive Catalogue of Rock Specimens in Jermyn Street Museum*, 3rd ed.; Prestwich, *Q. J. Geol. Soc.* x. p. 123; Whitaker, *Geological Survey Memoir on parts of Middlesex, &c.*, p. 71; J. W. Judd, *Geol. Mag.* 1901, p. 1; T. R. Jones, "History of the Sarsens," *op. cit.* pp. 54, 115.

[2] Barrois, *Ann. Soc. Géol. du Nord*, vi. p. 366.

exhibited among the "buttes" and "bad lands" of Wyoming and the neighbouring territories of North America (Fig. 103). Colossal pyramids, barred horizontally by level lines of stratification, rise up one after another far out into the plains, which were once covered by a continuous sheet of the formations whereof these detached outliers are only fragments.

As a consequence of this inequality in the rate of waste, depending on so many conditions, notably upon declivity, amount and heaviness of rain, lithological texture and composition, and geological structure, great varieties of contour are worked out upon the land. A survey of this department of geological activity shows, indeed, that the unequal wasting by rain has in large measure produced the details of relief on the present surface of the continents, those tracts where the destruction has been greatest forming hollows and valleys, others, where it has been less, rising into ridges and hills. Even the minuter features of crag and pinnacle may be referred to a similar origin. (Book VII.)

## § 2. Underground Water.[1]

A great part of the rain that falls on land, sinks into the ground and apparently disappears; the rest, flowing off into runnels, brooks and rivers, moves downward to the sea. It is most convenient to follow first the course of the subterranean water.

All rocks being more or less porous, and traversed by abundant joints and cracks, it results that from the bed of the ocean, from the bottoms of lakes and rivers, as well as from the general surface of the land, water is continually descending into the rocks beneath. To what depth this descent of surface-water may go, is not known. As stated in a former section, it may reach as far as the intensely heated interior of the planet, for, as the already quoted researches of Daubrée have shown, capillary water can penetrate rocks even against a high counter-pressure of vapour (*ante*, p. 410). Probably the depth to which the water descends varies indefinitely according to the varying nature of the rocky crust. Some shallow mines are practically quite dry, others of great depth require large pumping engines to keep them from being flooded by the water that pours into them from the surrounding rocks. Yet, as a rule, the upper layers of rock in the earth's crust are fuller of moisture than those deeper down.

Underground Circulation and Ascent of Springs.—The water which sinks below ground is not permanently removed from the surface, though there must be a slight loss due to absorption and chemical alteration of rocks. Finding its way through joints, fissures, or other divisional planes, it issues once more at the surface in springs. This may happen

[1] On this subject the following works are of value:—'Les Eaux souterraines aux Époques anciennes,' A. Daubrée, Paris, 1887; 'Les Eaux souterraines à l'Époque actuelle,' A. Daubrée, 2 vols., Paris, 1887; F. E. Suess, "Studien über unterirdische Wasserbewegung," *Jahrb. K. K. Geol. Reichsanst.* 1898, p. 425; F. H. King, "Principles and Conditions of the Movements of Ground-water," *19th Ann. Rep. U. S. G. S.* 1898, pp. 59-294; followed by a "Theoretical Investigation of the Motion of Ground-waters," by C. S. Schlichter, pp. 295-384; G. Jervis, 'I tesori sotteranei dell' Italia,' 4 vols. 1873-89.

either by continuous descent to the point of outflow, or by hydrostatic pressure. In the former case, rain-water, sinking underneath, flows along a subterranean channel until, when that channel is cut by a valley or other depression of the ground, the water emerges again to daylight. Thus, in a district having a simple geological structure (as in Fig. 104), a


Fig. 104.—Simple or Surface Springs.

sandy porous stratum (*d*), through which water readily finds its way, may rest on a less easily permeable clay (*e*), followed underneath by a second sandy pervious bed (*c*), resting as before upon comparatively impervious[1] strata (*a*). Rain falling upon the upper sandy stratum (*d*) will sink through it to the surface of the clay (*e*), along which it will flow until it issues either as springs, or in a general line of wetness along the side of the valley (*b*). The second sandy bed (*c*) will serve as a reservoir of subterranean water so long as it remains below the surface, but any valley cutting down below its base will drain it.

Except, however, in districts of gently inclined and unbroken strata, springs are more usually of the second class, where the water has descended to a greater or less distance, and has risen again to the surface in fissures, as in so many syphons. Lines of joint and fault afford ready channels for subterranean drainage (Fig. 105). Powerful faults

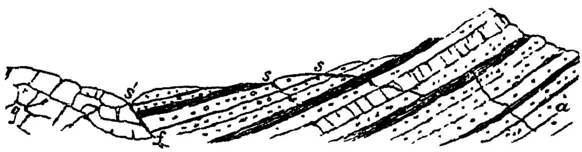



Fig. 105.—Deep-seated Springs (*s*, *s'*) rising through joints and a fault (*f*).

which bring different kinds of rock against each other (as *a* and *g* are by the fault *f* in Fig. 105) are frequently marked at the surface by copious springs. So complex is the network of divisional planes by which rocks are traversed, that water may often follow a most labyrinthine course before it completes its underground circulation (Fig. 106). In countries with a sufficient rainfall, rocks are saturated with water below a certain limit termed the *water-level*.[2] Owing to varying structure, and relative capacity for water among rocks, this line is not strictly horizontal, like

[1] This term *impervious* must evidently be used in a relative and not in an absolute sense. A stiff clay is practically impervious to the trickle of underground water; hence its employment as a material for puddling (that is, making water-tight) canals and reservoirs. But it contains abundant interstitial water, on which, indeed, its characteristic plasticity depends.

[2] On the underground saturation of rocks, see O. Keller, *Ann. Mines*, xii. (1897), p. 59; T. M. Reade, *Proc. Liverpool Geol. Soc.* 1883-84, "Experiments on the Circulation of Water in Sandstone." A body of information regarding the underground circulation of water in the permeable formations of England was collected by a Committee of the British Association, and will be found in the *Ann. Rep.* from 1875 onwards.

that of the surface of a lake. Moreover, it is liable to rise and fall according as the seasons are wet or dry.[1] In some places it lies quite near, in others far below, the surface. A well is an artificial hole dug

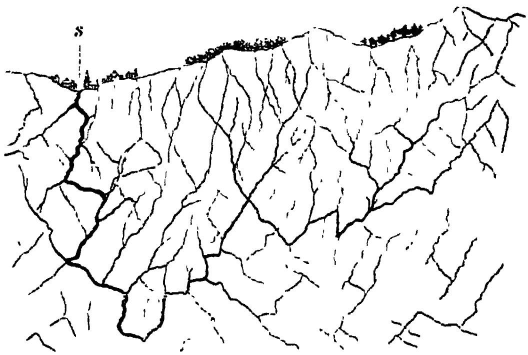


Fig. 106.—Intricate subterranean course of Percolating Water.

down below the water-level, so that the water may percolate into it. Hence, when the water-level happens to be at a small depth, wells are shallow; when at a greater depth, they require to be deeper.

Since rocks vary greatly in porosity, some contain far more water than others. It often happens that, percolating along some porous bed, subterranean water finds its way downward until it passes under some more impervious rock. Hindered in its progress, it accumulates in the porous bed, from which it may be able to find its way up to the surface again only by a tedious circuitous passage. If, however, a bore-hole be sunk through the upper impervious bed down to the water-charged stratum below, the water will avail itself of this artificial channel of escape, and will rise in the hole, or even gush out as a *jet d'eau* above ground. Wells of this kind are now largely employed. They bear the

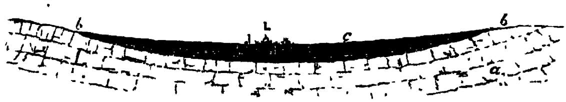


Fig. 107.—Diagram illustrative of the theory of Artesian Wells.
*a*, *b*, Lower water-bearing rocks, covered by an impervious series (*c*), through which, at L and elsewhere, borings are made to the water-level beneath.

name of *Artesian*, from the old province of Artois in France, where they have long been in use[2] (Fig. 107).

[1] It has been ascertained by observation and measurement that the discharge of springs is also affected by atmospheric pressure being greater with a low than with a high barometer. B. Latham, *Brit. Assoc.* 1881; see also *Geol. Mag.* 1893, p. 568.

[2] See Prestwich, *Q. J. Geol. Soc.* xxviii. p. lvii., and the references there given. On the subject of Artesian Wells, see Professor T. C. Chamberlin, *5th Ann. Rep. U. S. G. S.* (1883-84), p. 131; also "Final Report on Artesian and Underflow Investigation," *Ex. Doc. Senate U. S.* 41, part ii. (1892), p. 116; N. H. Darton, "Preliminary Report on Artesian Wells of a portion of the Dakotas," *17th Ann. Rep. U. S. G. S.* (1896); "Artesian Well Prospects in

That the water really circulates under ground, and passes not merely through the pores of the rocks, but in crevices and tunnels, which it has no doubt to a large extent opened for itself along natural joints and fissures, is proved by the occasional rise of leaves, twigs, and even live fish, in the shaft of an Artesian well. Such testimony is particularly striking when found in districts without surface-waters, and even perhaps with little or no rain. It has been met with, for instance, in sinking wells in some of the sandy deserts on the southern borders of Algeria.[1] In these and similar cases, it is clear that the water may, and sometimes does, travel for many leagues under ground, away from the district where it fell as rain or snow, or where it leaked from the bed of a river or lake.

The temperature of springs affords a convenient, but not always quite reliable, indication of the relative depth from which they have risen. Some springs are just one degree or less above the temperature of ice (C. 0°, Fahr. 32°). Others, in volcanic districts, issue with the temperature of boiling water (C. 100°, Fahr. 212°). Between these two extremes every degree may be registered. Very cold springs may be regarded as probably deriving their supply from cold or snow-covered mountains. Certain exceptional cases, however, occur, where, owing to the subsidence of the cold winter air into caverns (*glacières*), ice is formed which is not wholly melted even though the summer temperature of the caves may be above freezing-point. Water issuing from these ice-caves is of course cold.[2] On the other hand, springs whose temperature is higher than the mean temperature of the places at which they emerge must have been warmed by the internal heat of the earth. These are termed *Thermal Springs*.[3] The hottest springs are found in volcanic districts (see p. 315). But even at a great distance from any active volcano, springs rise with a temperature of 120° Fahr. (which is that of the Bath springs) or even more. These have probably ascended from a

the Atlantic Coast-plain Region," *Bull. U. S. G. S.* No. 138 (1896), p. 232; J. Gosselet, "Leçons sur les Nappes aquifères du Nord de la France," *Ann. Soc. Géol. Nord.* xiv. (1888), pp. 249-306.

[1] Desor, *Bull. Soc. Sci. Nat. Neufchâtel*, 1864. On the hydrology of the Sahara, consult G. Rolland, *Assoc. Française*, 1880, p. 547; Tchihatchef, *Brit. Assoc.* 1882, p. 356; Choisy, 'Documents relatifs à la Mission dirigée au Sud de l'Algérie,' Paris, 1890.

[2] A remarkable example of a glacière is that of Dobschau, in Hungary, of which an account, with a series of interesting drawings, was published in 1874 by Dr. J. A. Krenner, keeper of the National Museum in Buda-Pesth. See also Murchison, Keyserling and De Verneuil in 'Geology of Russia'; Thury, *Biblioth. Univ.*, Geneva, 1861; Browne, 'Ice-Caves in France and Switzerland,' 1865. Fifty-six of these caves are known in the Alps, some in the Jura, and many elsewhere. See also B. Schwalbe, *Central-Organ f. d. Interessen d. Realschul.* January 1884; H. Lohmann, 'Das Höhleneis unter besonderer Beruchtsichtigung einiger Eishöhlen des Erzgebirge,' Jena, 1895; *Nature*, xli. (1900), p. 591.

[3] Studer points out that some springs which are thermal in high latitudes, or at great elevations, would be termed cold springs near the equator, and, consequently, that springs having a lower temperature than that of the inter-tropical zone—that is, from C. 0° to 30° (Fahr. 32°-84°)—should be called "relative," those which surpass that limit (C. 30°-100°) "absolute," and he gives a series illustrative of each group: 'Physikalische Geographie,' ii. (1847), p. 49. For volcanic thermal springs, see *ante*, p. 315, and *postea*, p. 473.

great depth. If we could assume a progressive increase of 1° Fahr. of subterranean heat for every 60 feet of descent, the water at 120°, issuing at a locality whose ordinary temperature is 50°, should have been down at least 4200 feet below the surface. But from what has been already stated (p. 62) regarding the irregular stratification of temperature within the earth's crust, such estimates of the probable depth of the sources of springs are not quite reliable. The source of heat in these cases may be some crushing of the crust or ascent of heated matter from underneath, which has not, however, given rise to volcanic phenomena.

1. **Chemical Action.**[1]—Every spring, even the clearest and most sparkling, contains dissolved gases, also mineral solutions abstracted from the soils and rocks which it has traversed. The gases include those absorbed by rain from the atmosphere (pp. 414, 448), also carbon-dioxide supplied by decomposing organic matter in the soil, sulphuretted hydrogen, and marsh-gas or other hydrocarbon derived from decompositions within the crust. The dissolved solid constituents consist partly of organic, but chiefly of mineral matter. Where spring-water has been derived from an area covered with ordinary humus, organic matter is always present in it. Organic acids are abstracted from the soil by descending water, and these, before they are oxidised into carbonic acid, are effective in decomposing minerals and forming soluble salts (p. 450). The mineral matter of spring-water consists principally of carbonates of calcium, magnesium and sodium, sulphates of calcium and sodium, and chloride of sodium, with minute traces of silica, phosphates, nitrates, &c. The nature and amount of mineral impregnation depend, on the one hand, upon the chemical energy of the water, and on the other, upon the composition of the rocks.

Various sources of augmentation of its chemical energy are available for subterranean water:—(1) The abundant organic matter in the soil partially abstracts oxygen from the water, but supplies organic acids, especially carbonic acid. In so far as the water carries down from the soil any oxidisable organic substance, its action must be to reduce oxides (p. 451). Ordinary vegetable soil possesses the power of removing from permeating water potash, silica, phosphoric acid, ammonia and organic matter, elements which had been already abstracted from the soil by living vegetation, and which are again ready to be taken up by the same organic agents. (2) Carbon-dioxide is here and there largely evolved within the earth's crust, especially in regions of extinct or dormant volcanoes. Subterranean water coming in the way of this gas dissolves it, and thereby obtains increased solvent power. (3) The capacity of water for dissolving mineral substances is augmented by increase of temperature (*ante*, p. 411). It is conceivable that cold springs, containing a large percentage of mineral solutions, may have acquired this impregnation at a great depth and at a higher temperature. As a rule, however, thermal water, as it cools, deposits more or less of its dissolved minerals on the walls of the fissures up which it ascends. Hence, no doubt, the

[1] This subject is fully treated in vol. ii. of Daubrée's 'Les Eaux souterraines à l'Époque actuelle.'

successive layers in mineral veins. (4) Pressure likewise raises the solvent power of water (p. 411). (5) Some of the solutions, due to decompositions effected by the water, increase its ability to accomplish further decompositions (p. 414). Thus the alkaline carbonates, which are among the earliest products, enable it to dissolve silica and decompose silicates. These carbonates likewise promote the decomposition of some sulphates and chlorides. Calcium-carbonate, which is found in the water of most springs, is the result of decomposition, and by its presence leads to the further disintegration of various minerals. "Carbonic acid, bicarbonate of lime, and the alkaline carbonates bring about most of the decompositions and changes in the mineral kingdom. It is a matter of great importance to find that the same substances which give rise to so many decompositions in the mineral kingdom are the chief ingredients in the waters." [1]

The nature of the changes effected by the percolation of water through subterranean rocks will be best understood from an examination of the composition of spring-water. Springs may be conveniently, though not very scientifically, grouped into two classes: 1st, common springs, such as are fit for ordinary domestic purposes, although always containing more or less mineral matter in solution; and 2nd, mineral springs, in which the proportions of dissolved mineral matter are so much higher as to remove the water from the usual potable kinds.

1. Common Springs possess a temperature not higher but frequently lower than that of the localities at which they rise, and ordinarily contain, besides atmospheric air and its gases, calcium-carbonate and sulphate, common salt, with chlorides of calcium and magnesium, and sometimes organic matter. The amount of dissolved mineral contents in ordinary drinking-water does not exceed 0·5, or at most 1·0 gramme per litre; the best waters contain less. The amount of organic matter should not exceed from 0·005 to 0·01 gramme per litre in wholesome drinking-water.[2] Spring-water containing a very minute percentage of mineral matter, or in which this matter, even if in more considerable quantity, consists chiefly of alkaline salts, dissolves common soap readily, and is known in domestic economy as "soft" water. Where, on the other hand, the salts in solution are calcic or magnesic carbonates, sulphates, or chlorides, they decompose soap, forming with its fatty acids insoluble compounds which appear in the familiar white curdy precipitate. Such water is termed "hard." Where the hardness is due to the presence of bicarbonates it disappears on boiling, owing to the loss of carbonic acid and the consequent precipitation of the insoluble carbonate; while in the case of sulphates and chlorides no such change takes place.

The extensive investigations carried on by the Rivers Pollution Commission in Britain have thrown much light on the relation between the amount of mineral matter in solution in springs and wells, and the character of the underlying rock. The following table of analyses of waters from different kinds of rocks gives a summary of results obtained:—

| | No. of Analyses. | Mean amount of Solid Contents in 10,000 parts of Water. |
|---|---|---|
| 1. Fluviomarine, Drift and Gravel | 10 | 6·132 |
| 2. Chalk | 30 | 2·984 |
| 3. Hastings Sand and Greensands | 19 | 3·005 |
| 4. Oolites | 35 | 3·033 |

[1] Bischof, 'Chem. Geol.' i. p. 17.

[2] Dr. B. H. Paul in Watts' 'Dict. Chem.' v. p. 1022.

| | No. of Analyses. | Mean amount of Solid Contents in 10,000 parts of Water. |
|---|---|---|
| 5. Lias | 7 | 3·641 |
| 6. New Red Sandstone | 15 | 2·869 |
| 7. Magnesian Limestone | 1 | 6·652 |
| 8. Coal-measures | 14 | 2·430 |
| 9. Yoredale beds and Millstone-grit | 8 | 1·773 |
| 10. Mountain Limestone | 13 | 3·206 |
| 11. Devonian and Old Red Sandstone | 32 | 2·506 |
| 12. Silurian | 15 | 1·233 |
| 13. Granite and Gneiss | 8 | 0·594 |

From this table it is evident how greatly the proportion of dissolved mineral substance augments in those waters which rise in calcareous tracts, and how it correspondingly sinks in those where the rocks are mainly siliceous. The maximum percentage in group No. 13 was less than 1 part in every 10,000 of water, the minimum being 0·140 from granite. In No. 1, on the contrary, the maximum was 22·524, in No. 6 it was 7·426, and in No. 10 it was 9·850.[1]

2. Mineral Springs are in some instances cold, in others warm, or even boiling. Thermal springs are more usually mineral waters than cold springs, but there does not appear to be any necessary relation between temperature and chemical composition. Mineral springs may be roughly classified for geological purposes according to the prevailing mineral substance contained in them, which may range in amount from 1 to 300 grammes per litre.[2]

*Calcareous Springs* contain calcium-carbonate in such quantity as to be deposited in the form of a white crust round objects over which the water flows. Calcium-carbonate, according to Fresenius, is dissolved by 10,600 of cold and by 8834 parts of warm water.[3] But in nature, the proportion of this carbonate present in springs depends mainly on the proportion of free carbonic acid, which retains the lime in solution. On the loss of carbonic acid by exposure and evaporation, the carbonate is thrown down as a white precipitate. This deposition is frequently brought about by the action of living plants. (Book III. Part II. Sect. iii. § 3.) Water saturated with carbonic acid will at the freezing-point dissolve 0·70 gramme and at 10° C. 0·88 gramme of calcium-carbonate per litre. Calcareous springs occur abundantly in limestone districts, and indeed may be looked for wherever the rocks are of a markedly calcareous character. In some regions, they have brought up such enormous quantities of lime as to form considerable hills (*postea*, p. 475).

*Ferruginous or Chalybeate Springs* contain a large proportion of ferrous sulphate (iron-

[1] *Rivers Pollution Commission*, *6th Report*, 1874, pp. 107-131. See also Reports of Brit. Assoc. Committee on Underground Circulation of Water, beginning in 1876; and R. Warington's Report on experiments at the Rothamsted Laboratory, *Journ. Chem. Soc.* 1887.

[2] Paul, Watts' 'Dict. Chem.' v. p. 1016. Daubrée, from the chemical side, groups them in seven divisions:—1st, with sodium-chloride either alone or with other chlorides or with sulphates or carbonates; here also come some springs with magnesium or calcium-chloride; 2nd, with hydrochloric acid found at active volcanic centres; 3rd, sulphuretted; 4th, with free sulphuric acid; 5th, with sulphates of sodium, calcium, magnesium; aluminous, ferrous or ferric; 6th, carbonated, containing carbonate of soda, or of lime, iron, magnesia or more complex compounds; 7th, silicated. The mineral springs of the United States are described by A. C. Peale, *Bull. U. S. G. S.* No. 32 (1886), p. 235; see also *14th Ann. Rep. U. S. G. S.* (1892-93). Besides their mineral solutions, many springs contain considerable amounts of dissolved gases. Prof. W. Ramsay obtained argon and helium from a number of mineral waters examined by him: *Proc. Roy. Soc.* 1897.

[3] Roth, 'Chem. Geol.' i. p. 48. "One litre of water, either cold or boiling, dissolves about 18 milligrammes." Roscoe and Schorlemmer, 'Chemistry,' ii. p. 208.

vitriol, copperas) in the total mineral ingredients, and are known by their inky taste, and the yellow, brown or red ochry deposit along their channel. They may be frequently observed in districts where beds or veins of pyritous ironstone occur, or where the rocks contain much iron-disulphide in combination, particularly in the waters of old mines. By the weathering of this sulphide (marcasite), so abundantly contained among stratified rocks, ferrous sulphate is produced and brought to the surface, but in presence of carbonates, particularly of the ubiquitous carbonate of lime, is decomposed, the acid being taken up by the alkaline earth or alkali, and the iron becoming a ferrous carbonate, which rapidly oxidises and falls as the familiar yellow or brown crust of hydrous peroxide. The rapidity with which ferrous-carbonate is thus oxidised and precipitated was well shown by Fresenius in the case of the Langenschwalbach chalybeate spring. In its fresh state the water contains in 1000 parts 0·37696 of protoxide of iron. After standing twenty-four hours it was found to contain only 87·7 per cent of the original amount of iron; after sixty hours 62·9 per cent, and after eighty-four hours 53·2 per cent.[1]

*Brine-Springs* (Soolquellen) bring to the surface a solution in which sodium chloride greatly predominates. Springs of this kind appear where beds of solid rock-salt exist underneath, or where the rocks are impregnated with that mineral. Most of the brines worked as sources of salt are derived from artifical borings into saliferous rocks. Those of Cheshire in England, the Salzkammergut in Austria, Bex in Switzerland, &c., have long been well known. That of Clemenshall, Würtemberg, yields upwards of 26 per cent of salts, of which almost the whole is chloride of sodium. The other substances contained in solution in the water of brine-springs are chlorides of potassium, magnesium and calcium; sulphates of calcium, and less frequently of sodium, potassium, magnesium, barium, strontium or aluminium; silica; compounds of iodine and fluorine; with phosphates, arseniates, borates, nitrates, organic matter, carbon-dioxide, sulphuretted hydrogen, marsh-gas and nitrogen.[2]

*Medicinal Springs*, a vague term applied to mineral springs which have or are believed to have curative effects in different diseases. Medical men recognise various qualities, distinguished by the particular substance most conspicuous in each variety of water—*Alkaline Waters*, containing lime or soda and carbonic acid—Vichy,[3] Saratoga; *Bitter Waters*, with sulphate of magnesia and soda—Sedlitz, Kissingen; *Salt* or *Muriated Waters*, with common salt as the leading mineral constituent—Wiesbaden, Cheltenham; *Earthy Waters*, lime, either a sulphate or carbonate being the most marked ingredient —Bath, Lucca; *Sulphurous Waters*, with sulphur as sulphuretted hydrogen and in sulphides—Aix-la-Chapelle, Harrogate. Some of these medicinal springs are thermal waters. Even where no longer warm, the water may have aquired its peculiar medicinal characters at a great depth, and therefore under the influence of increased temperature and pressure. Sulphur springs are sometimes warm, but also occur abundantly cold, where the water rises through rocks containing decomposing sulphides and organic matter. Sulphates are there first formed, which by the reducing effect of the organic matter are decomposed, with the resultant formation of sulphuretted hydrogen (p. 92). Sulphuretted hydrogen and sulphurous acid are sometimes oxidised into sulphuric acid, which remains free in the water.[4]

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[1] *Journal für prakt. Chem.* lxiv. p. 368, quoted by Roth, *op. cit.* i. p. 565. The river in the Vale of Avoca, Ireland, formerly contained so much ferrous sulphate, carried into it by mine-waters, that its bed and banks for several miles down to the sea were covered with an ochreous deposit.

[2] Roth, 'Chem. Geol.' i. p. 442. Bischof, 'Chem. Geol.' ii. Many subterranean waters, though not deserving the name of brines, contain considerable proportions of chlorides. On the alkaline chlorides of the Coal-measures, see R. Malherbe, *Bull. Acad. Roy. Belgique*, 1875, p. 16; also R. Laloy, *Ann. Soc. Géol. Nord*, 1875, p. 195.

[3] See G. F. Dollfus, 'Recherches géologiques sur les Environs de Vichy,' Paris, 1894.

[4] Roth, *op. cit.* i. pp. 444, 452.

*Hot Springs, Geysers.*—The thermal waters of volcanic districts usually contain a marked percentage of dissolved mineral matter, notably silica, with sulphates, carbonates, chlorides, bromides, and other combinations. Perhaps the most detailed examination yet made of any such group of springs is the series of analyses performed by the Geological Survey of the United States on the waters of forty-three hot springs in the Yellowstone National Park. The temperatures of these waters ranged up to 93° C., and the total amount of dissolved mineral matter up to 2·8733 grammes in every kilogramme. The silica sometimes amounted to 0·6070 gramme, the sulphuric acid to 1·9330, the carbonic acid to 1·2490, the chlorine to 1·0442, the calcium to 0·3076, the magnesium to 0·0797, the potassium to 0·1603, the sodium to 0·4407, and there were minute quantities of numerous other constituents.[1] It has been ascertained that in these springs, also, fresh-water algæ play a considerable part in the production of the sinter. (See Book III. Part II. Sect. iii. § 3.)

*Oil Springs.*—Petroleum is sometimes brought up in drops floating in spring-water (St. Catherine's, near Edinburgh). In many countries it comes up by itself or mingled with inflammable gases. Reference has already been made (pp. 185, 318) to the abundance of this product in North America. In western Pennsylvania, some oil-wells have yielded as much as 2000 to 3000 barrels of oil per day.[2]

**Results of the Chemical Action of Underground Water.**—Three remarkable results of the chemical operations of underground water are:—1st, The internal composition and minute structure of rocks are altered. 2nd, Enormous quantities of mineral matter are carried up to the surface, where they are partly deposited in visible form, and partly conveyed by brooks and rivers to the sea. 3rd, As a consequence of this transport, subterranean tunnels, passages, caverns, grottos, and other cavities of many varied shapes and dimensions are formed.

(1) *Alteration of rocks.*—The processes of oxidation, deoxidation, solution, hydration, and the formation of carbonates, described (pp. 450-453) as carried on above ground by rain, are likewise in progress on a great scale underneath. Since the permeability of subterranean rocks permits water to find its way through their pores as well as along their divisional planes, chemical changes, of a kind like those in ordinary weathering, take place in them, and at some depth may be intensified by internal terrestrial heat and pressure. This subterranean alteration of rocks may consist in the mere addition of substances introduced in chemical solution; in the simple solution and removal of some one or more constituents: or in a complex process of removal and replacement, wherein the original substance of a rock is molecule by molecule removed, while new ingredients are simultaneously or afterwards substituted. In tracing these alterations of rocks, the study of pseudomorphs becomes important, for we thereby learn what was the original composition of the mineral or rock. The mere existence of a pseudomorph points to the removal and substitution of mineral matter by permeating water.[3]

[1] F. A. Gooch and J. E. Whitfield, *Bull. U. S. Geol. Survey*, No. 47, 1888.

[2] See the authorities cited *ante*, p. 319.

[3] It is not needful to take account here of such exceptional cases as the artificial conversion of aragonite into calcite by exposure to a high temperature. In such paramorphs the change is a molecular or crystalline rather than a chemical one, though how it takes place is still unknown. Pseudomorphs may be artificially formed. Crystals of atacamite

The extent to which such mineral replacement has been carried among rocks of the most varied structure and composition is probably best shown by the abundant petrified organic forms in formations of all geological ages. The minutest structures of plants and animals have been, particle by particle, removed and replaced by mineral matter introduced in solution, and this so imperceptibly, and yet thoroughly, that even minutiæ of organisation, requiring a high power of the microscope for their investigation, have been preserved without distortion or disarrangement. From this perfect condition of preservation, gradations may be traced until the organic structure is gradually lost amid the crystalline or amorphous infiltrated substance (Fig. 108). The most important petrifying media in nature are calcium-carbonate, silica and iron-disulphide (marcasite more usually than pyrite). (See Book V.)

Fig. 108.—Fossil Wood from tuff, Burntisland, showing parts perfectly preserved and parts destroyed by crystallisation of calcite. Magnified 10 diameters.

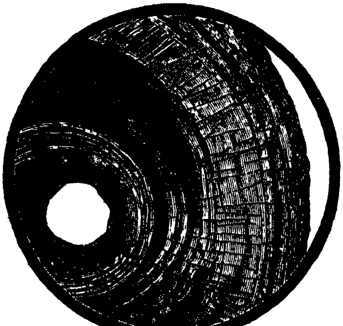

Fig. 109.—Section of a part of a Stalactite Magnified 10 diameters.

Another proof of the alteration which rocks have suffered from permeating water is supplied by the abundance of veins of calcite and quartz by which they are traversed, these minerals having been introduced in solution and often from the decomposition of the enclosing rock. As Bischof pointed out, a drop of acid seldom fails to give effervescence on pieces of rock, composed of silicates, which have been taken even at some little depth from the surface, thus indicating the decomposition and deposit caused by permeating water. As already stated, one of the most remarkable results of the application of the microscope to geological inquiry is the extent to which it has revealed these all-pervading alterations, even in what might be supposed to be perfectly fresh rocks. Among the silicates, the most varied and complex interchanges have been effected. Besides the production of calcium-carbonate by the decomposition of such minerals as the lime-felspars, the series of hydrous green ferruginous silicates (delessite, saponite, chlorite, serpentine, &c.), so commonly met with in crystalline rocks, are usually witnesses to the

($Cu_4O_3Cl_2 + 4H_2O$) placed in a solution of bicarbonate of soda are completely changed into malachite in four years. *Tschermak's Min. Mitth.* 1877, p. 97.

influence of infiltrating water. The changes visible in olivine (pp. 103, 242) offer instructive lessons on the progress of transformation. One further example may be cited as supplied by the zeolites, so common in cavities and veins among many ancient volcanic and other crystalline rocks. These have commonly resulted from the decomposition of felspars or allied minerals. Their mode of formation is indicated by the observation already cited (p. 411), that Roman masonry at the baths of Plombières has in the course of centuries been so decomposed by the slow percolation of alkaline water at a temperature not exceeding 50° C. (122° Fahr.) under ordinary atmospheric pressure, that various zeolitic silicates have been developed in the brick.[1]

(2) *Chemical deposits.*—Of these by far the most abundant is calcium-carbonate. The way in which this substance is removed and re-deposited by permeating water can be instructively studied in the formation of the familiar *stalactites* and *stalagmites* beneath damp arches and in limestone caves (p. 191). As each drop gathers on the roof and begins to evaporate and lose carbonic acid, the excess of carbonate which it can no longer retain is deposited round its edges as a ring (Fig. 109). Drop succeeding drop, the original ring grows into a long pendant tube, which, by subsequent deposit inside and outside, becomes a solid stalk, and on reaching the floor may thicken into a massive pillar. At first the calcareous substance is soft and, when dry, pulverulent, but by prolonged saturation and the internal deposit of calcite it becomes by degrees crystalline. Each stalactite is found to possess an internal radiating fibrous structure, the fibres (prisms) passing across the concentric zones of growth (p. 191). The stalactite remains saturated with calcareous water, and the divergent prisms are developed and continued as radii from the centre of the stalk. This process may be completed within a short period. At the North Bridge, Edinburgh, for example, which was erected in 1772, stalactites were obtained in 1874, some of which measured an inch and a half in diameter and possessed the characteristic radiating structure.[2] It is doubtless by an analogous process that limestones, originally composed of the débris of calcareous organisms and interstratified among perfectly unaltered shales and sandstones, have acquired a crystalline structure (p. 156).[3]

Some calcareous springs deposit abundantly a precipitate of carbonate of lime upon mosses, twigs, leaves, stones and other objects. The precipitate takes place when from any cause the water parts with carbonic acid. This may arise from mere evaporation, but is frequently due to the action of bog-mosses and water-plants, which, decomposing the

[1] Daubrée, 'Géologie expérimentale,' p. 179 *et seq.* As already mentioned (*ante*, p. 411), the formation of zeolites can be effected even by snow-water.

[2] The rate of deposit in the Ingleborough Cave is stated to be ·2946 inch per annum, or about 2½ feet in a century (Boyd Dawkins, *Brit. Assoc.* 1880, Sects. p. 573). This is probably an exceptionally rapid growth.

[3] Sorby, Address to Geological Society, *Q. J. Geol. Soc.* 1879, p. 42 *et seq.* The finely fibrous structure seen in chalcedony under the microscope with polarised light passes in a similar way through the bands of growth of pebbles.

carbonic acid, cause a crust of carbonate of lime to be deposited round their stems and branches (*postea*, p. 611). Hence calcareous springs are popularly called "petrifying," though they merely encrust organic bodies, and do not convert them into stone. Calc-sinter or travertine, as this precipitate is called, may be found in course of formation in most limestone districts, sometimes in masses large enough to form hills, and compact enough to furnish excellent building-stone. The travertine of Tuscany is deposited at the Baths of San Vignone at the rate of six inches a year, at San Filippo one foot in four months. At the latter locality it has been piled up to a depth of at least 250 feet, forming a hill a mile and a quarter long and a third of a mile broad.[1] An instructive illustration of the rapidity with which the travertine may be deposited is furnished by the Eocene sinter of Sezanne, Marne. This deposit contains hollow casts of flowers which fell on the growing sinter, and were crusted over with it before they had time to wither. As the material thickened round them they decayed inside, but the hardened carbonate preserved an accurate mould of their forms. When hot wax is injected into these cavities, and the surrounding lime is dissolved away with acid, perfect casts of the flowers are obtained.

Chalybeate springs give rise to a deposit of hydrous peroxide of iron. This has already been referred to as a yellow and reddish-brown deposit along the channels of the water. Some acidulous springs, like those of the Laacher See, deposit large quantities of ochre. In undrained districts of temperate latitudes, as in Northern Europe and America, much iron is also deposited beneath soil which rests on a retentive subsoil. When the descending water is arrested on this subsoil, the iron, in solution as organic salts that oxidise into ferrous carbonate, is gradually converted into the insoluble hydrous ferric oxide, which is precipitated and forms a dark ferruginous layer, known to Scottish farmers as "moorband pan." So effectually does this layer interrupt the drainage that the soil remains permanently damp and unfertile. But when the "pan" is broken up and spread over the surface it quickly disintegrates, and improves the soil, which can then be properly drained (*postea*, p. 612).

Siliceous springs form important masses of sinter round the point of outflow. The basins and funnels of geysers have already been described (p. 315). One of the sinter-beds in the Iceland geyser region is said to be two leagues long, a quarter of a league wide, and a hundred feet thick. Enormous beds of similar material have been formed in the Yellowstone geyser region. Such accumulations usually point to proximity to former volcanic centres, and are formed during one of the latest phases of volcanic action.

[1] Lyell, 'Principles,' i. p. 402. At Narni, the greater the velocity of flow, the greater the deposit of lime, very little being deposited in stagnant water. The amount thrown down increases with temperature and distance from source, exposure to the air being necessary for deposition. B. Fabri, *Proc. Inst. Civ. Engineers*, xli. (1876), p. 246. The student will find much detail regarding the abstraction and deposit of carbonate of lime by subterranean water in a paper by Senft, "Die Wanderungen und Wandelungen des kohlensäuren Kalkes," *Z. D. G. G.* xiii. p. 263.

(3) *Formation of subterranean channels and caverns.*—Measurement of the yearly amount of mineral matter brought up to the surface by a spring, furnishes an approximate idea of the extent to which underground rocks undergo continual loss of substance. The warm springs of Bath, for example, with a mean temperature of 120° Fahr., are impregnated with sulphates of lime and soda, and chlorides of sodium and magnesium. Sir A. C. Ramsay estimated their annual discharge of mineral matter to be equal to a square column 9 feet in diameter and 140 feet in height. Again, the St. Lawrence spring at Louèche (Leuk) discharges every year 1620 cubic metres (2127 cubic yards) of dissolved sulphate of lime, equivalent to the lowering of a bed of gypsum one square kilometre (0·3861 square mile) in extent, more than 16 decimetres (upwards of five feet) in a century.[1]

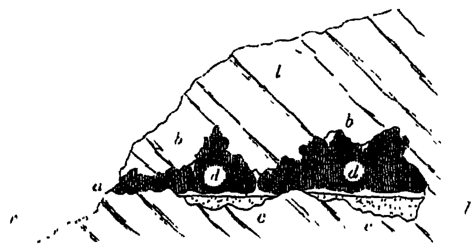


Fig. 110.—Section of a Limestone Cavern (*B.*).

*l l*, A limestone hill, perforated by a cavern (*b b*) which communicates with the valley (*c*) by an opening (*a*). The bottom of the cavern is covered with ossiferous loam, above which lies a layer of stalagmite (*d d*), while stalactites hang from the roof, and by joining the floor separate the cavern into two chambers.

By prolonged abstraction of this nature, subterranean tunnels, channels and caverns have been formed. In regions abounding in rock-salt deposits, the result of the solution and removal of these by underground water is visible in local sinkings of the ground and the consequent formation of pools and lakes. The landslips and meres of Cheshire are illustrations of this process. In that county, owing to the pumping out of the brine in the manufacture of salt, tracts of ground sometimes more than 100 acres in extent have sunk down and become the sites of lakes of varying depth, some being 45 feet deep.[2] In calcareous districts, still more striking effects are observable. The ground may there be found drilled with vertical cavities (*swallow-holes*, *sinks*, *dolinas*), by the solution of the rock along lines of joint or of faults that serve as channels for descending rain-water. The line of outcrop of a limestone-band, among non-calcareous strata, may often be traced, even under a covering of superficial deposits, by its row of swallow-holes. Surface-drainage, thus intercepted, passes at once under ground, where, in course of time, an elaborate system of spacious tunnels

[1] E. Reclus, 'La Terre,' i. p. 340.

[2] T. Ward, "History and Cause of the Subsidences at Northwich, &c." 1887, *Geol. Mag.* 1887, p. 517.

and chambers may be dissolved out of the solid rock (Fig. 112).[1] Such has been the origin of the Peak caverns of Derbyshire, the intricate grottos of Antiparos and Adelsberg, and the vast labyrinths of the Mammoth Cave of Kentucky.[2] In the course of time, the underground rivers open out new courses, and leave their old ones dry, as the Poik has done at Adelsberg. By the falling in of the roofs of caverns, or the widening of the fissures that reach up to the soil, a communication is established with the surface, and land-shells and land-animals fall into the holes,[3] or the caverns are used as dens by beasts of prey, so that the remains of terrestrial animals are preserved under the stalagmite. Not unfrequently caverns, once open and freely used as haunts of carnivora, have had their entrances closed by the fall of débris, as at *d* in Fig. 111, where also the

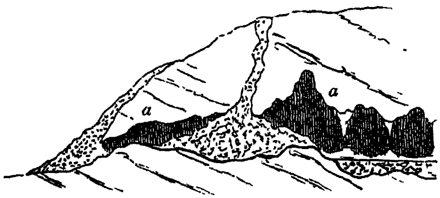


Fig. 111.—Section of a Limestone Cavern with fallen-in roof and concealed entrance (*B.*).

partial filling up of a cavern (*a a*) from the same cause is seen. Where the collapse of a cavern roof takes place below a water-course, the stream is engulfed. In this way, brooks and rivers suddenly disappear from the surface, and after a long subterranean course issue again in a totally different surface-area of river-drainage from that in which they took their rise, and sometimes with volume enough to be navigable almost up to their outflow. In such circumstances, lakes, either temporary, like the Lake Zirknitz in Carniola, or perennial, may be formed over the sites of the broken-in caverns; and valleys may thus be deepened, or gorges may be formed.[4] Mud, sand and gravel, with the remains of plants and animals, are swept below ground, and sometimes

[1] For accounts of the remarkable honeycombed region of Carniola, &c., see Mojsisovics, 'Geologie von Bosnien-Hercegovina,' pp. 44-60; *Zeitsch. Deutsch. Alpenvereins*, 1880. E. Tietze, *Jahrb. Geol. Reichsanst.* xxx. (1880), p. 729, and papers cited by him. E. Reyer, "Studien über das Karst-relief," *Mitt. Geograph. Ges.*, Vienna, 1881. C. Viola, "La Struttura Carsica," *Boll. Com. Geol. Ital.* xxviii. (1897), p. 147. A. Parat on this structure in the Cure and Yonne, *Congr. Géol. Internat. Paris*, 1900, p. 419. E. Dupont on the Han-Rochefort district of Belgium, *Ann. Soc. Belg. Géol.* tome vii. 1893.

[2] For a popular account of caves, see F. Kraus, "Höhlenkunde," Vienna, 1894; H. Kloos and Max Müller have published an account with photographs of the Herman's Cave of Rübeland in Brunswick (Weimar, 1889).

[3] As a good example of this result, the Ightham fissure and its abundant animal remains may be cited, *Q. J. G. S.* l. (1894), pp. 171-187, 188-211, where the investigations of Messrs. Abbot and Newton are given. Various other instances will be cited in Book VI.

[4] See interesting accounts by M. Martel of the subterranean channels of the Causses or Jurassic limestone plateaux of Gard and Lozère in the south of France, and of the formation of cañons there. *Compt. rend.* 1888. *B. S. G. F.* xvii. (1889), p. 610.

accumulate in deposits of loam and breccia, such as are so often found in ossiferous caverns (Figs. 110, 111).

As from time to time the roofs of underground chambers, weakened by the constant abstraction of mineral matter, collapse, or large portions are detached from them and fall on the floors below, sudden shocks are generated which are felt above ground as earthquakes. In subsiding to

Fig. 112.—Section of the Channel of an Underground Stream.

fill up hollows from which the rock has been removed in solution, the overlying strata may be greatly contorted and fractured, those underneath remaining undisturbed.

2. **Mechanical Action.**—In its passage along fissures and channels, underground water not merely dissolves and removes mineral substances in solution, it likewise loosens finer particles and carries them along in mechanical suspension. This removal of material sometimes produces remarkable surface-changes along the sides of steep slopes or cliffs. A thin porous layer, such as loose sand or ill-compacted sandstone, lying between more impervious rocks, such as masses of clay or limestone, and sloping down from higher ground, so as to come out to the surface near the base of a line of abrupt cliff, serves as a channel for underground water which issues in springs or in a more general oozing at the foot of the declivity. Under these circumstances the support of the overlying mass of rock is apt to be loosened; for the water not only removes piece-

meal the sandy layer on which that overlying mass rests, but, as it were, lubricates the rock underneath. Consequently, at intervals, portions of the upper rock break off and slide down into the valley or plain below. Such dislocations are known as *landslips* or *landslides*.[1] The movement may be gradual, as in the case of the Bec Rouge in the Tarentaise, where the side of the mountain is slowly overwhelming the village of Miroir,[2] or it may be sudden and disastrous.

Where landslips have been started initially by a shattering of the ground during an earthquake shock (*ante*, p. 372), the subsequent progress of slipping may be largely due to the influence of underground water and general atmospheric disintegration. Illustrations of this combination of causes resulting in extensive disturbance of the sides of mountains and valley slopes appear to be furnished by the high grounds of Colorado so well described by Mr. Whitman Cross.[3]

Along sea-coasts and river-valleys at the base of cliffs subject to continual or frequent removal of material by running water, the phenomena of landslips are best seen. The coast-line of the British Islands abounds with instructive examples. On the shores of Dorsetshire, for instance (Fig. 113), impervious Liassic clays (*a*) are overlain by porous greensand (*b*), above which lies chalk (*c*) capped with gravel (*d*). In consequence of the percolation of water through the sandy zone (*b*), the support of the overlying mass is destroyed, and hence, from time to time, segments are launched down towards the sea. In this way, a confused medley of mounds and hollows (*f*) forms a characteristic strip of ground termed the "Undercliff" on this and other parts of the English coasts. This recession of the upper or inland cliff through the operation of springs is here more rapid than that of the lower cliff (*g*) washed by the sea.[4] In the year 1839, after a season of wet weather, a mass of chalk on the same coast slipped over a bed of clay into the sea, leaving a rent three-quarters of a mile long, 150 feet deep, and 240 feet wide. The shifted mass, bearing with it houses, roads, and fields, was cracked, broken, and tilted in various directions, and was thus prepared for further attack and removal by the waves.[5] In February 1891 a mass of chalk-cliff calculated to contain some 10,000 tons of material gave way on the cliffs to the east of Brighton, and fell to the beach, breaking

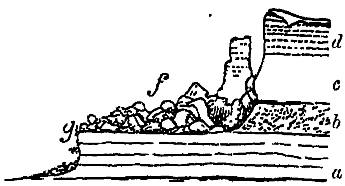

Fig. 113.—Section of Landslip forming undercliff, Pinhay, Lyme-Regis (*B.*).

[1] Baltzer, in his work, "Ueber Bergstürze in den Alpen" (Zürich, 1875), classifies Swiss landslips into four categories, viz.: 1st, Rock-falls (Felsstürze); 2nd, Earth-slips (Erdschliffe); 3rd, Mud-streams (Schlammströme), where soft strata saturated with water are crushed by the weight of overlying rock and move down in mass, like lava; 4th, Mixed falls (gemischte Stürze), where, as in most instances, rock, earth, and mud are launched down the declivities. More recently he has offered another classification of landslips, according to the dimensions of the mass moved and the solid or muddy condition of the material: *Neues Jahrb.* 1880 (ii.), p. 198. See A. Rothpletz, *Z. D. G. G.* 1881, p. 540; also *op. cit.* 1882, pp. 430, 435. E. Buss and A. Heim, 'Der Bergsturz von Elms,' Zurich, 1881.

[2] L. Borrell, *B. S. G. F.* sér. 3, vi. (1877), p. 47.

[3] *21st Ann. Rep. U. S. G. S.* 1900, pp. 129-157.

[4] De la Beche, 'Geol. Observer,' p. 22.

[5] Conybeare and Buckland's 'Axmouth Landslip,' London, 1840. Lyell, 'Principles,' i. p. 536.

away part of the main road above. In March 1893, by an extensive slipping of the Lower Greensand towards the beach, a large part of the town of Sandgate on the coast of Kent was destroyed. The antiquity of many landslips is shown by the ancient buildings occasionally to be seen upon the fallen masses. The undercliff of the Isle of Wight, the cliffs west of Brandon Head, county Kerry, the basalt escarpments of Antrim, and the edges of the great volcanic plateaux of Mull, Skye and Raasay, furnish illustrations of such old and prehistoric landslips.

On a more imposing scale, and interesting from its melancholy circumstances being so well known, was the celebrated fall of the Rossberg, a mountain (*a*, Fig. 114) situated behind the Rigi in Switzerland, rising to a height of more than 5000 feet above the sea. After the rainy summer of 1806, a large part of one side of the mountain, consisting of steeply sloping beds of hard red sandstone and conglomerate (*b*), resting upon soft sandy layers (*c c*), gave way. The lubrication of the lower surface by the water having loosened the cohesion of the overlying mass, thousands of tons of solid rock, set loose by mere gravitation, suddenly swept across the valley of Goldau (*d*), burying about a square German mile of fertile land, four villages containing 330 cottages and outhouses, with 457 inhabitants.[1] In 1855 a mass of débris, 3500 feet long, 1000 feet wide, and 600 feet high, slid into the valley of the Tiber, which, dammed back by the obstruction, overflowed the village of San Stefano to a depth of 50 feet, until drained off by a tunnel.

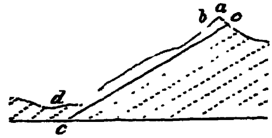

Fig. 114.—Section illustrating the fall of the Rossberg.

Gigantic landslips have from time to time taken place on the line of the Canadian Pacific Railway. Owing to irrigation of the sides of the valley of the Thompson River, the upper sandy deposits that overlie the boulder-clay become saturated and finally give way, rushing down to the river below. In 1881 one slide was estimated to contain a mass of 100,000,000 tons of dislodged material.[2] The heavy rainfall of India frequently gives rise to extensive and disastrous landslips.[3]

## § 3. Brooks and Rivers.

These will be considered under four aspects:—(1) sources of supply, (2) discharge, (3) flow, and (4) geological action.[4]

1. **Sources of Supply.**—Rivers, as the natural drains of a land-surface, carry out to sea the surplus water after evaporation, together with a vast amount of material worn off the land. Their liquid contents are derived partly from rain (including mist and dew) and melted snow, partly from springs. In a vast river-system, like that of the Mississippi, where the area of drainage is so extensive as to embrace different climates and varieties of rainfall, the amount of discharge, being in a great measure independent of local influences of weather, remains

[1] Zay, 'Goldau und seine Gegend.' Baltzer, *Neues Jahrb.* 1875, p. 15. Upwards of 150 destructive landslips have been chronicled in Switzerland. Riedl, *Neues Jahrb.* 1877, p. 916.

[2] R. B. Stanton, *Min. Proc. Inst. Civ. Engin.* cxxxii. (1897).

[3] Accounts of these are to be found in the Reports of the *Geol. Surv. India*; *Nature*, l. (1894), p. 231. For descriptions of Norwegian landslips, see No. 27 of the Reports of the *Norges Geol. Undersøg.* by P. J. Friis (1898) and H. Reusch in Aarbog for 1900.

[4] An excellent monograph on a river is C. Lenthéric's 'Le Rhône, Histoire d'un Fleuve,' 2 vols., Paris, 1892. See also 'River Development as illustrated by the Rivers of N. America,' by I. C. Russell (Progressive Science Series), pp. xv, 327.

tolerably uniform, or is subject to regular, periodically recurrent variations. In smaller rivers, such as those of Britain, whose basins lie in a region having the same general features of climate, the quantity of water is regulated by the local rainfall. A wet season swells the streams, a dry one diminishes them. Hence, in estimating and comparing the geological work done by different rivers, we must take into account whether or not the sources of supply are liable to occasional great augmentation or diminution. In some rivers, there is a more or less regularly recurring season of flood followed by one of drought. The Nile, fed by the spring rains of Abyssinia, floods the plains of Egypt every summer, rising in Upper Egypt from 30 to 35 feet, at Cairo 23 to 24 feet, and in the seaward part of the delta about 4 feet. The Ganges and its adjuncts begin to rise every April, and continue doing so until the plains are converted into a vast lake 32 feet deep. In other rivers, sudden and heavy rains, occurring at irregular intervals, swell the usual volume of water and give rise to floods, freshets or "spates." This is markedly the case with the rivers of Western Europe. Thus the Rhône sometimes rises 11½ feet at Lyons and 23 feet at Avignon; the Saône from 20 to 24½ feet. In the middle of March 1876, the Seine rose 20 feet at Paris, the Oise 17 feet near Compiègne, the Marne 14 feet at Damery. The Ardèche at Gournier exceeded a rise of 69 feet during the inundations of 1827.[1] The causes of floods, not only as regards meteorological conditions, but in respect to the geological structure of the ground, merit the careful attention of the geological student. He may occasionally observe that, other things being equal, the volume of a flood is less in proportion to the permeability of a hydrographic basin, and the consequent ease with which rain can sink beneath the surface.

Were rivers entirely dependent upon direct supplies of rain, they would only flow in rainy seasons and disappear in drought. This does not happen, however, because they derive much of their water not directly from rain, but indirectly through the intermediate agency of springs. Hence they continue to flow even in very dry weather, because, though the superficial supplies have been exhausted, the underground sources still continue available. In a long drought, the latter begin at length to fail, the surface springs ceasing first, and gradually drying up in their order of depth, until at last only deep-seated springs furnish a perhaps daily diminishing quantity of water. Though it is a matter of great economic as well as scientific interest to know how long any river would continue to yield a certain amount of water during a prolonged drought, no rule seems possible for a generally applicable calculation, every area having its own peculiarities of underground drainage, and

[1] For a graphic account of rivers swollen by heavy rainfall, see Sir T. D. Lauder's 'Morayshire Floods.' On torrents, consult Surell and Cézanne, 'Études sur les Torrents des Hautes Alpes.' The rivers of the United States have been made the subject of detailed observation for some years past, and the voluminous results of their measurements will be found in the volumes containing the hydrographic work of the Geological Survey. See for example *18th Ann. Rep.* (1898), where more than 400 pages are devoted to the subject. The 19th and 20th Reports are even more copious. See also *Bulletins*, Nos. 131 and 140.

varying greatly from year to year in the amount of rain which is absorbed. The river Wandle, for instance, drains an area of 51 square miles of the chalk downs in the south-east of England. For eighteen months, from May 1858 to October 1859, as tested by gauging, there was very little absorption of rainfall over the drainage basin, and yet the minimum recorded flow of the Wandle was 10,000,000 gallons a day, which represents not more than ·4090 inch of rain absorbed on the 51 square miles of chalk. The rock is so saturated that it can continue to supply a large yield of water for eighteen months after it has ceased to receive supplies from the surface, or at least has received only very much diminished supplies.[1]

2. **Discharge.**—What proportion of the total rainfall is discharged by rivers is another question of great geological and industrial interest. From the very moment that water takes visible form, as mist, cloud, dew, rain, snow or hail, it is subject to evaporation. When it reaches the ground, or flows off into brooks, rivers, lakes or the sea, it undergoes continual diminution from the same cause. Hence in regions where rivers receive no tributaries, they grow smaller in volume as they move onward, till in dry, hot climates they even disappear. Apart from temperature, the amount of evaporation is largely regulated by the nature of the surface from which it takes place, one soil or rock differing from another, and all of them probably from a surface of water. Full and detailed observations are still wanting for determining the relation of evaporation to rainfall and river discharge.[2] During severe storms of rain, the water discharged over the land finds its way, to a very large extent, at once into brooks and rivers, by which it reaches the sea. Mr. David Stevenson remarks that, according to different observations, the amount carried off

[1] Lucas, 'Horizontal Wells,' London, 1874, pp. 40, 41. See also Braithwaite, *Min. Proc. Inst. Civ. Engin.* xx. Lawes and Gilbert, on the percolation of rain through soils and chalk, *Min. Proc. Inst. Civ. Engin.* xlv. p. 208 ; see also Greaves, *op. cit.* p. 19. Gilbert, *op. cit.* cv. (1891), part iii.

[2] In the present state of our information it seems almost useless to state any of the results already obtained, so widely discrepant and irreconcilable are they. In some cases, the evaporation is given as usually three times the rainfall : and that evaporation always exceeded rainfall was for many years the belief among the French hydraulic engineers. (See *Annales des Ponts-et-Chaussées*, 1850, p. 383.) Observations on a larger scale, and with greater precautions against the undue heating of the evaporator, have since shown that as a rule, save in exceptionally dry years, evaporation is lower than rainfall. As the average of ten years from 1860 to 1869, Mr. Greaves found that at Lea Bridge the evaporation from a surface of water was 20·946 inches, while the rainfall was 25·534 (Symons's *British Rainfall* for 1869, p. 162). On the great plains of the United States, where, outside of the humid belt, the climate is dry, the average annual evaporation, under the most favourable condition of a free water surface, largely exceeds the total annual precipitation, being in some places as much as 54·6 inches against 20·4 inches of rainfall. The excess is observable even in the wheat-growing north-west. On the other hand, at New Orleans the conditions are reversed, the rainfall amounting there to 60·3 inches, while the evaporation falls to 45·4 inches. W. D. Johnson, *21st Ann. Rep. U. S. G. S.* 1901, part iv. "Hydrography," p. 677. But we still need an accumulation of observations, taken in many different situations and exposures, in different rocks and soils, and at various heights above the sea. (For a notice of a method of trying the evaporation from soil, see *British Rainfall*, 1872, p. 206.)

in floods varies from 1 to 100 cubic feet per minute per acre.[1] In estimating and comparing, therefore, the ratios between rainfall and river discharge in different regions, regard must be had to the nature of the rainfall, whether it is crowded into a rainy season or diffused over the year. Thus, though floods cannot be deemed exceptional phenomena, forming as they do a part of the regular system of water-circulation over the land, they do not represent the ordinary proportions between rainfall and river discharge in such a climate as that of Britain, where the rainfall is spread more or less equally throughout the year. According to Beardmore's table,[2] the Thames at Staines has a mean annual discharge of 32·40 cubic inches per minute per square mile, equal to a depth of 7·31 inches of rainfall run off, or less than a third of the total rainfall. The data, carefully collected by Humphreys and Abbot for the basin of the Mississippi and its tributaries, are shown in the subjoined table:[3]—

| | Ratio of Discharge to Rainfall. |
|---|---|
| Ohio River | 0·24 |
| Missouri River | 0·15 |
| Upper Mississippi River | 0·24 |
| Small Tributaries | 0·90 |
| Arkansas and White River | 0·15 |
| Red River | 0·20 |
| Yazoo River | 0·90 |
| St. Francis River | 0·90 |
| Entire Mississippi, exclusive of Red River | 0·25 |

In the Mississippi basin, one-fourth of the rainfall is thus discharged into the sea. The Elbe, from the beginning of July 1871 to the end of June 1872, was estimated to carry off at most a quarter of the rainfall from Bohemia.[4] The Seine at Paris appears to carry off about a third of the rainfall. In Great Britain from a fourth to a third part of the rainfall is perhaps carried out to sea by streams.[5]

In comparing also the discharges of different rivers, regard should be paid to the influence of geological structure, and particularly of the permeability or impermeability of the rocks, as regulating the supply of water to rivers. Thus the Thames, from a catchment basin of 3670 square miles and with a rainfall of 27 inches, has a mean annual discharge at Kingston of 1250 millions of gallons a day, and rather more than 688 millions of gallons in summer. The Severn, on the other hand, which gathers its

1 'Reclamation and Protection of Agricultural Land,' Edin. 1874, p. 15.

2 'Hydrology,' p. 201. Comp. Report of Royal Commission on Water Supply, 1869, p. liii.

3 'Physics and Hydraulics of the Mississippi River,' Washington, 1861, p. 136. For recent detailed measurements of the discharge of rivers in the United States, see the series of hydrographic reports above cited. The last of these reports (*21st Ann. Rep.* 1901, part iv.) contains a voluminous record and discussion of the subject.

4 *Verhandl. Geol. Reichsanstalt*, Vienna, 1876, p. 173.

5 In mountainous tracts having a large rainfall and a short descent to the sea, the proportion of water returned to the sea must be very much greater than this. Mr. Bateman's observations for seven years in the Loch Katrine district gave a mean annual rainfall of 87½ inches at the head of the lake, with an outflow equivalent to a depth of 81·70 inches of rain removed from the drainage basin of 71½ square miles. See a paper by Graeve on the quantity of water in German rivers, and on the relation between rainfall and discharge, *Der Civil-Ingenieur*, 1879, p. 591; *Nature*, xxiii. p. 94. J. Murray, *Scott. Geog. Mag.* 1887.

supplies mainly from the hard, impervious slate hills of Wales, has a drainage area above Gloucester of 3890 square miles, with an average rainfall of probably not less than 40 inches. Yet its daily summer discharge does not amount to 298 millions of gallons, and its minimum sinks as low as 100 millions of gallons, while that of the Thames in the driest season never falls below 350 millions. In the one case, the water is stored up within the rocks and is dispensed gradually; in the other, it in great measure runs off at once.[1] It is likewise deserving of note that the operations of man, particularly in draining land and deforesting, may materially alter the mean level of a river and increase the volume of floods. The mean level of the Elbe at Dresden is said to have been perceptibly diminished by human interference, while in the Rhine the low-water level has been lowered, and the floods have been augmented.[2] The quantity of water poured into the sea by the larger rivers of the globe varies with the season of the year. The River Plate was estimated by Bateman to discharge in dry weather 670,000 cubic feet per second, a quantity equal to the mean volume of thirty-three years passing down the Mississippi, while the mean flood of the Amazons varies from 2,700,000 to 3,510,000 cubic feet per second, or thirty-three times the volume of the Nile.[3]

3. **Flow.**—While, in obedience to the law of gravitation, a river always flows from higher to lower levels, great variations in the rate and character of its motion are caused by inequalities in the angle of slope of its channel. A vertical or steeply inclined face of rock originates a waterfall; a rocky declivity in the channel gives rise to rapids; a flat plain allows the stream to linger with a scarcely visible current; while a lake renders the flow nearly or altogether imperceptible. Thus the rate of flow is regulated in the main by the angle of inclination and form of the channel, but partly also by the volume of water, an increase of volume in a narrow channel increasing the rate of motion even without an increase of slope.[4]

The course of a great river may be divided into three parts: (1) *The Mountain Track,*—where, amidst clouds or snows, it takes its rise as a mere brook, and, fed by innumerable similar torrents, dashes rapidly down the steep sides of the mountains, leaping from crag to crag in endless cascades, and growing every moment in volume, until it enters lower ground. (2) *The Valley Track,*—where, now flowing through lower hills or undulations, the stream is found at one time in a wide fertile valley, then in a dark gorge, now falling headlong into a cataract, now expanding into a broad lake. This is the part of its career where it assumes the most varied aspects, and receives the largest tributaries. (3) *The Plain Track,*—where, having quitted the undulating region, the river finally emerges upon broad plains, probably wholly or in great part composed of alluvial formations deposited by its own waters. Here winding sluggishly in wide curves, it may eventually bifurcate, as it approaches the sea and spreads through its delta, enclosing tracts of flat meadow or marsh, and finally, amid banks of mud and sand, passing out into the great ocean. In Europe, the Rhine, Rhône and Danube; in

[1] Prestwich, *Q. J. Geol. Soc.* xxviii. p. lxv. Compare the conditions of the catchment basin of the Seine as given by A. Delaire, *Ann. Conserv. Arts et Métiers*, No. 138, p. 335.

[2] "Report of (Austrian) Committee on Diminution of Water in Springs and Rivers," *Proc. Inst. Civ. Engineers*, xlii. (1875), p. 271.

[3] T. Mellard Reade, "Rivers," *Trans. Liverpool Geol. Soc.* 1882.

[4] See A. Tylor on the laws of river-action, *Geol. Mag.* 1875, p. 443.

Asia, the Ganges and Indus; in America, the Mississippi and Amazon; in Africa, the Nile and Niger—illustrate this typical course of a great river.

If we draw a longitudinal section of the course of any such river or of any of its tributaries from its source, or from the highest peaks around that source, to its mouth, we find that the line at first curves steeply from the mountain crests down into the valleys, but grows less and less inclined through the middle portion, until it finally can hardly be distinguished from a horizontal line. This feature, however, is not confined to stream courses, but belongs to the architecture of the continents.

It is evident that a river must flow, on the whole, fastest in the first portion of its course, and slowest in the last. The common method of comparing the fall or slope of rivers is to divide the difference of height between their source and the sea-level by their length, so as to give the declivity per mile. This mode, however, often fails to bring out the real resemblances and differences of rivers, even in regard to their angle of slope. For example, two streams rising at a height of 1000 feet, and flowing 100 miles to the sea, would each have an average slope of 10 feet per mile; yet they might be wholly unlike each other, one making its descent almost entirely in the first or mountain part of its course, and lazily winding for most of its way through a vast low plain; the other toiling through the mountains, then keeping among hills and table-lands, so as to form on the whole a tolerably equable and rapid flow. The great rivers of the globe have probably a less average slope than 2 feet per mile, or 1 in 2640. The Missouri, which has a descent of 28 inches per mile, is a tumultuous rapid current even down as far as Kansas City. The average slope of the channel of the Thames is 21 inches per mile; of the Shannon about 11 inches per mile, but between Killaloe and Limerick about 6½ feet per mile; of the Nile, below Cairo, 3·25 to 5·5 inches per mile; of the Doubs and Rhône, from Besançon to the Mediterranean, 24·18 inches per mile; of the Volga from its source to its mouth, a little more than 3 inches per mile. Higher angles of descent are those of torrents, as the Arve, with a slope of 1 in 616 at Chamounix, and the Durance, whose angle varies from 1 in 467 to 1 in 208. The Colorado river rushes through its cañons with an average declivity of 7·72 feet per mile, or 1 in 683. The slope of a navigable river ought hardly to exceed 10 inches per mile, or 1 in 6336.[1]

But not only does the rate of flow of a river vary at different parts of its course, it is not the same in every part of the cross-section of the river taken at any given point. A river channel (Fig. 115) supports a succession of layers of water (*a*, *b*, *c*, *d*), moving with different velocities, the greatest movement being at the centre (*d*), and the least in the layer which lies directly on the channel. At the same vertical depth, therefore, the velocity is greater in proportion as the point approaches the centre of the stream. The water next the sides and bottom (*a a*), being retarded by friction against the channel, moves less rapidly than the layers (*b b*, *c c*) towards the centre (*d*). The central piers of a bridge have consequently

[1] D. Stevenson, 'Canal and River Engineering,' p. 224.

a greater velocity of river-current to bear than those at the banks. The motion of the surface-water, however, is retarded, on the other hand, by upward currents, generated chiefly by irregularities of the bottom.[1] It follows that whatever tends to diminish the friction of the moving current will increase its rate of flow. The same body of water, other conditions being equal, will move faster through a narrow gorge with steep smooth walls than over a broad, rough, rocky bed. For the same reason, when two streams join, their united current, having in many cases a channel not much larger than that of one of the single streams, flows faster, because the water encounters now the friction of only one channel. The average rate of flow is much less than might be supposed, even in what are termed swift rivers. A moderate current is about 1¼ mile in the hour; even that of a torrent does not exceed 18 or 20 miles in the hour. Mr. D. Stevenson states that the velocity of such rivers as the Thames, the Tay or the Clyde may be found to vary from about one mile per hour as a minimum to about three miles per hour as a maximum velocity.[2]

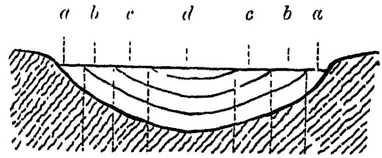

Fig. 115.—Cross-section of a River.

It may be remarked, in concluding this part of the subject, that elevations and depressions of land must have a powerful influence upon the slopes of rivers. The upraising of the axis of a country, by increasing the slope, augments the rate of flow, which, on the contrary, is diminished by a depression of the axis or by an elevation of the maritime regions.

4. **Geological Action.**—Like all other forms of moving water, streams have both a *chemical* and *mechanical* action. The latter receives most attention, as it undoubtedly is the more important; but the former ought not to be omitted in any survey of the general waste of the earth's surface.

i. Chemical.—The water of rivers must possess the powers of a chemical solvent, like rain and springs, though its actual work in this respect can be less easily measured, seeing that river-water is directly derived from rain and springs, and necessarily contains in solution mineral substances supplied to it by them. Nevertheless, that streams dissolve chemically the rocks of their channels can be strikingly seen in limestone districts, where the lower portions of the ravines may be found enlarged into wide cavities or pierced with tunnels and arches, presenting in their smooth surfaces a great contrast to the angular, jointed faces of the same rock where exposed to the influence only of the weather.[3]

Daubrée endeavoured to illustrate the chemical action of rivers upon their transported pebbles by exposing angular fragments of felspar to prolonged friction in revolving cylinders of sandstone containing distilled water. He found that they underwent considerable decomposition, as was shown by the presence of silicate of potash, rendering the

[1] J. Thomson, *Proc. Roy. Soc.* xxviii. (1878), p. 114. Comp. Collignon, 'Cours d'Hydraulique,' p. 301.

[2] 'Reclamation of Land,' p. 18.

[3] For an illustration of this action by the Rhône in the marine molasse, see F. Cuvier, *Bull. Soc. Géol. France*, 3me sér. viii. p. 164.

water alkaline. Three kilogrammes of felspar fragments made to revolve in an iron cylinder for a period of 192 hours, which was equal to a journey of 460 kilometres (287 miles), yielded 2·720 kilogrammes of mud, while the five litres of water in which they were kept moving contained 12·60 grammes of potash, or 2·52 grammes per litre.[1]

The mineral matter held in solution in river-water is, doubtless, partly derived from the mechanical trituration of rocks and detritus; for Daubrée's experiments show that minerals which resist the action of acid may be slowly decomposed by mere mechanical trituration, such as takes place along the bed of a river. But in sluggish streams the main supply of mineral solution is doubtless furnished by springs.

The proportion of mineral matter in river-water varies with the season, even for the same stream. It reaches its maximum when the water is mainly derived from springs, as in very dry weather and during frost; it attains its minimum in rainy seasons and after rain.[2] Its amount and composition depend upon the nature of the rocks forming the drainage-basin. Where these are on the whole impervious, the water runs off with comparatively slight abstraction of mineral ingredients; but where they are permeable, the water, in sinking through them and rising again in springs, dissolves their substance and carries it into the rivers.

The composition of the river-waters of Western Europe is well shown by numerous analyses. The substances held in solution include variable proportions of the atmospheric gases, carbonates of lime, magnesia, soda, iron and ammonia; silica; peroxides of iron and manganese; alumina; sulphates of lime, magnesia, potash and soda; chlorides of sodium, potassium, calcium and magnesium; silicate of potash; nitrates; phosphoric acid; and organic matter. The minimum proportion of mineral matter among the analyses collected by Bischof was 2·61 in 100,000 parts of water in the Möll, near Heiligenblut—a mountain stream 3800 feet above the sea, flowing from the Pasterzen glacier over crystalline schists. On the other hand, as much as 54·5 parts in the 100,000 were obtained in the waters of the Beuvronne, a tributary of the Loire above Tours. The average of the whole of these analyses is about 21 parts of mineral matter in 100,000 of water, whereof carbonate of lime usually forms the half, its mean quantity being 11·34.[3] Bischof calculated that, assuming the mean quantity of carbonate of lime in the Rhine to be 9·46 in 100,000 of water, which is the proportion ascertained at Bonn, enough of this substance is carried into the sea by this river for the annual formation of three hundred and thirty-two thousand millions of oyster-shells of the usual size. The mineral next in abundance is sulphate of lime, which in some rivers constitutes nearly half of the dissolved mineral matter. Less in amount are sodium chloride,[4] magnesium carbonate and sulphate, and silica. Of the last-named, a percentage amounting to 4·88 parts in 100,000 of water has been found in the Rhine, near

[1] 'Géologie expérimentale,' p. 271; Fayol, *Bull. Soc. Géol. France*, 3me sér. xvi. p. 996. See *postea*, p. 496.

[2] Roth, 'Chem. Geol.' i. p. 454.

[3] Bischof, 'Chem. Geol.' i. chap. v. Of the analyses, chiefly of European rivers, published by Roth, the mean of thirty-eight gives a proportion of 19·983 in 100,000 parts of water. *Op. cit.* p. 456. Compare I. C. Russell, *Bull. U. S. Geol. Surv.* 1889; A. Delebecque on the composition of the Dranse and Rhône, *Compt. rend.* 1894, p. 36; J. Hanamann, "Die chemische Beschaffenheit der fliessenden Gewässer Böhmens," *Archiv Nat. Landesdurchf. Böhmen*, 1894.

[4] On the variations of the chlorine in the Nile and Thames, see J. A. Wanklyn, *Chem. News*, xxxii. (1875), pp. 207, 219.

Strasburg.[1] The largest amount of alumina was 0·71 in the Loire, near Orleans. The proportion of mineral matter in the Thames, near London, amounts to about 33 parts in 100,000 of water.[2]

It requires some reflection properly to appreciate the amount of solid mineral matter which is every year carried in solution from the rocks of the land and diffused by rivers into the sea. Accurate measurements of the amount of material so transported are still much required. The Thames carries past Kingston 19 grains of mineral salts in every gallon, or 1502 tons every twenty-four hours, or 548,230 tons every year. Of this quantity about two-thirds consist of carbonate of lime, the rest being chiefly sulphate of lime, with minor proportions of the other ordinary salts of river-water. Prestwich estimated that the quantity of carbonate of lime removed from the limestone areas of the Thames basin amounts to 140 tons annually from every square mile. This quantity, assuming a ton of chalk to measure 15 cubic feet, is equal to a loss of $\frac{8}{100}$ of an inch from each square mile in a century, or one foot in 13,200 years.[3] According to monthly observations and estimates made in the year 1866 at Lobositz, near the exit of the Elbe from its Bohemian basin, this river may be regarded as carrying every year out of Bohemia from an area of 880 German square miles, or, in round numbers, 20,000 English square miles, 6,000,000,000 cubic metres of water, containing 622,680,000 kilogrammes of dissolved and 547,140,000 of suspended matter, or a total of 1169 millions of kilogrammes. Of this total, 978 millions of kilogrammes consist of fixed and 192 millions of volatile (chiefly organic) matter. The proportions of some of the ingredients most important in agriculture were estimated as follows: lime, 140,380,000 kilogrammes; magnesia, 28,130,000; potash, 54,520,000; soda, 39,600,000; chloride of sodium, 25,320,000; sulphuric acid, 45,690,000; phosphoric acid, 1,500,000.[4] The Nile in 1874 was ascertained to contain a proportion of dissolved mineral matter which varied from 13·614 to 20·471 in every 100,000 parts of water, thus carrying down 41 times more matter in solution in flood than when the river is low.[5]

Mr. T. Mellard Reade has estimated that a total of 8,370,630 tons of solids in solution is every year removed by running water from the rocks of England and Wales, which is equivalent to a general lowering of the surface of the country, from that cause alone, at a rate of ·0077 of a foot in a century, or one foot in 12,978 years. The same writer computes the annual discharge of solids in solution by the Rhine to be equal to 92·3 tons per square mile, that of the Rhône at Avignon 232 tons, that of the Danube 72·7 tons, and that of the Mississippi 120 tons. He supposes that on an average over the whole world there may be every year dissolved by rain about 100 tons of rocky matter per English square mile of surface.[6]

If the average proportion of mineral matter in solution in river-water be taken as only 2 parts in every 10,000 by weight, then it is obvious that in every 5000 years the rivers of the globe must carry to the sea their own weight of dissolved rock.

[1] Of the total solid matter dissolved in the water of the river Uruguay as much as about 46 per cent consists of soluble silica, chiefly as hydrated silicic acid. Hence the "petrifying" property of the water. J. Kyle, *Chem. News*, xxxviii. (1878), p. 28.

[2] Bischof, *op. et loc. cit.*; Roth, *op. cit.* i. p. 454. For composition of British river-water, see *Rivers Pollution Commission Report*, cited on p. 449.

[3] *Q. J. G. S.* xxviii. p. lxvii.

[4] Breitenlohner, *Verhand. Geol. Reichsanst.*, Vienna, 1876, p. 172. Taking the 978,000,000 kilogrammes to be mineral matter in solution and suspension, this is equal to an annual loss of about 48 tons per English square mile. But it includes all the materials discharged by the drainage of an abundant population.

[5] T. Mellard Reade, *Trans. Liverpool Geol. Soc.* 1882.

[6] Addresses, *Liverpool Geol. Soc.* 1876 and 1884.

ii. Mechanical.—The mechanical work of rivers is threefold: (1) to transport mud, sand, gravel or blocks of stone from higher to lower levels; (2) to use these loose materials in eroding their channels; and (3) to deposit the sediment where possible, and thus to make new geological formations.[1]

1. *Transporting Power.*[2]—One of the distinctions of river-water, as compared with that of springs, is that as a rule it is less transparent—in other words, contains more or less mineral matter in suspension.[3] A sudden heavy shower, or a season of wet weather, suffices to render turbid a river which was previously clear. The mud is washed into the main streams by rain and brooks, but is partly produced by the abrasion of the water-channels through the operations of the streams themselves. The channels of the mountain-tributaries of a river are choked with large fragments of rock disengaged from cliffs and crags on either side. Traced downwards, the blocks become gradually smaller and more rounded. They are ground against each other and upon the rocky sides and bottom of the channel, becoming more and more reduced as they descend, and at the same time abrading the rocks over or against which they are driven. Of the detritus thus produced, the finer portions are carried in suspension, and impart the characteristic turbidity to rivers; the coarser sand and gravel are driven along the river-bottom.[4]

The presence of a moving stratum of coarse detritus on the bed of a brook or river may be detected in transit, for, though invisible beneath the overlying discoloured water, the stones of which it is composed may be heard knocking against each other as the current sweeps them onward. Above Bonn, and again a little below the Lurelei Rock, while drifting down the Rhine, the observer, by laying his ear close to the bottom of the open boat, may hear the harsh grating of the gravel-stones over each other, as the current pushes them onwards along the bottom. On the Moselle also, between Cochem and Coblentz, the same fact may be noticed.

[1] On the behaviour of rivers, consult Dausse, 'Études relatives aux Inondations,' Paris, 1872.

[2] See Login, *Nature*, i. pp. 629, 654; ii. p. 72.

[3] The brown colour of river or estuary water is not always due to mud. In the Southampton Water it is caused in summer by the presence of protozoa (*Peredinium fuscum*). A. Angell, *Brit. Assoc.* 1882, Sects. p. 589.

[4] These operations of running water may be studied with great advantage on a small scale, where brooks descend from high grounds into valleys, rivers or lakes. A single flood suffices for the transport of thousands of tons of stones, gravel, sand and mud, even by a small streamlet. At Lybster, for example, on the coast of Caithness, as the author was informed by Mr. Thomas Stevenson, C.E., a small streamlet carries down annually into a harbour which has there been made, between 400 and 500 cubic yards of gravel and sand. A weir or dam has been constructed to protect the harbour from the inroad of the coarser sediment, and this is cleaned out regularly every summer. But by far the greater portion of the fine silt is no doubt swept out into the North Sea. The erection of the artificial barrier, by arresting the seaward course of the gravel, reveals to us what must be the normal state of this stream and of similar streams descending from maritime hills. The area drained by the stream is about four square miles; consequently the amount of loss of surface, which is represented by the coarse gravel and sand alone, is $\frac{1}{9100}$ of a foot per annum.

The transporting capacity of a stream depends (*a*) on the volume and velocity of the current, (*b*) on the size, shape, and specific gravity of the sediment, and (*c*) partly on the chemical composition of the water. (*a*) According to the calculations of Hopkins,[1] the capacity of transport increases as the sixth power of the velocity of the current; thus the motive power of the current is increased 64 times by the doubling of the velocity, 729 times by trebling, and 4096 times by quadrupling it. If a stream which, in its ordinary state, can just move pebbles weighing an ounce, has its velocity doubled by a flood, it can then sweep forward stones weighing 4 lb. Mr. David Stevenson[2] gives the subjoined table of the power of transport of different velocities of river currents:—

| In. per Second. | | Mile per Hour. | |
|---|---|---|---|
| 3 | = | 0·170 | will just begin to work on fine clay. |
| 6 | = | 0·340 | will lift fine sand. |
| 8 | = | 0·4545 | will lift sand as coarse as linseed. |
| 12 | = | 0·6819 | will sweep along fine gravel. |
| 24 | = | 1·3638 | will roll along rounded pebbles 1 inch in diameter. |
| 36 | = | 2·045 | will sweep along slippery angular stones of the size of an egg. |

It is not the surface velocity, nor even the mean velocity, of a river which can be taken as the measure of its power of transport, but the bottom velocity—that is, the rate at which the stream overcomes the friction of its channel. (*b*) The average specific gravity of the stones in a river ranges between two and three times that of pure fresh water; hence these stones when borne along by the river lose from a half to a third of their weight in air. Huge blocks which could not be moved by the same amount of energy applied to them on dry ground, are swept along when they have found their way into a strong river-current. The shape of the fragments greatly affects their portability, when they are too large and heavy to be carried in mechanical suspension. Rounded stones are of course most easily transported: flat and angular ones are moved with comparative difficulty (see p. 496). (*c*) Pure water will retain fine mud in suspension for a long time; but the introduction of mineral matter in solution diminishes its capacity to do so, probably by lessening the molecular cohesion of the liquid. Thus the mingling of salt with fresh water causes a rapid precipitation of the suspended mud (p. 511). Probably each variety of river-water has its own capacity for retaining mineral matter in suspension, so that the mere mingling of these varieties may be one cause of the precipitation of sediment.[3] In some experiments made

[1] *Q. J. Geol. Soc.* viii. p. xxvii.

[2] 'Canal and River Engineering,' p. 315. See also Thoulet, *Ann. des Mines*, 1884, p. 507.

[3] T. Sterry Hunt, *Proc. Boston Nat. Hist. Soc.* 1874; W. Durham, *Chem. News*, xxx. (1874), p. 57; xxxvii. (1878), p. 47; W. Ramsay, *Quart. Journ. Geol. Soc.* xxxii. (1876), p. 129; C. Barus, *Bull. U. S. Geol. Surv.* No. 36 (1886), No. 60 (1890), p. 189; Thoulet, *Ann. des Mines*, xix. (1891), p. 5. In this last memoir M. Thoulet concludes as the result of his experiments that the precipitation of clays takes place in fresh water which has had an addition of 10 per cent of sea-water (and consequently of density equal to 1·002) exactly as in pure sea-water, and that this observation furnishes a measure for determining the true

by Mr. L. F. Vernon-Harcourt it was found that silt from the Dnieper took 20 minutes to subside one foot in distilled water, 13 minutes in water from the Thames, 12 minutes in water from the sea, and only 4 minutes in a saturated solution of sea-salt. Silt from the Nile treated in the same way sank at the rates of 3 days, 20 minutes, 13 minutes and 10 minutes respectively; while in the case of silt from the Mississippi the rates were 57 minutes, 36 minutes, 30 minutes and 9 minutes.[1]

Besides inorganic sediment, rivers may contain a large amount of organic matter. The most obvious examples of this part of their contents are furnished by the enormous vegetable accumulations on some of the larger rivers. The "sudd" of the White Nile is a thick mass of growing vegetation, which overspreads and conceals the river and has been a great impediment to navigation, though a track has now been cut through it.[2] The rafts of the Mississippi, Amazon, Orinoco, Congo and Ganges are other familiar illustrations. Even where the raft begins by the accumulation of drift-wood, when embayed or arrested in midstream, it is soon covered with living vegetation, and these floating islands may remain for many years, rising and sinking with the water that supports them. The Atchafalaya has been so obstructed by drift-wood as to be fordable like dry land, and the Red River for more than a hundred miles flows under a matted cover of dead and living vegetation. From time to time these floating islands break loose from their moorings and are borne down by the current. They are sometimes seen fifty or a hundred miles out at sea away from the mouth of the Ganges. By this means of transport the plants and animals of the land may be carried to distant shores, or their remains may be dispersed over the sea-floor.[3]

But besides these larger forms of life, minute organisms sometimes constitute a considerable proportion of the so-called "solid impurity" of river-water. The mud of the Ganges, for instance, is estimated to contain from 12 to 25 per cent of infusoria, and that of the Nile 4·6 to 10 per cent.[4]

Beyond their ordinary powers of transport, rivers gain at times con-

limits of the ocean and the continents. See also L. F. Vernon-Harcourt, "Experimental Investigations on the action of Sea-water in accelerating the deposit of River-silt and the formation of Deltas," *Min. Proc. Inst. Civ. Engin.* cxlii. (1900), part iv. This subject is now undergoing investigation by Professor Joly, "The Inner Mechanism of Sedimentation,—Preliminary Note," *Sci. Proc. Roy. Dublin Soc.* ix. (1900), p. 325. See *postea*, p. 511.

[1] *Op. cit.* p. 10. This observer experimented also with solutions of various strengths of some of the prevalent salts of the water of rivers and the sea, and found that sulphates of calcium and magnesium, and the chlorides of potassium and magnesium, surpass sodium-chloride in their influence in the precipitation of fine mechanical sediment.

[2] "The Sudd of the White Nile," *Geog. Journ.* xv. (1900), p. 234.

[3] Lyell, 'Principles,' vol. ii. p. 361.

[4] Ehrenberg long ago remarked that the calcareous polythalamia carried into the sea by the Tiber were *marine* forms (*Bericht Akad. Berlin*, 1855); and more recently Professor Sollas has shown that in the chalk districts of England there is a perceptible transport of undissolved coccoliths, foraminifers and other Cretaceous organisms carried in suspension in the streams. *Geol. Mag.* 1900, p. 248. On the inundations of the Tiber, E. Clerici, *Boll. Soc. Geol. Ital.* xx. (1901), p. 131.

siderable additional force from several causes. Those liable to sudden and heavy falls of rain, or to a rapid augmentation of their volume by the quick melting of snow, acquire by flooding an enormous increase of transporting and excavating power. More work may thus be done by a stream in a day than could be accomplished by it during months of its ordinary condition.[1] Another cause of sudden increase in the efficacy of river-action is provided when, from landslips formed by earthquakes, by the undermining influence of springs, or otherwise, a stream is temporarily dammed back, and the barrier subsequently gives way. The bursting out of the arrested waters produces great destruction in the valley. Blocks as big as houses may be set in motion, and carried down for considerable distances. Again, the transporting power of rivers may be greatly augmented by frost (see *postea*, p. 532). Ice forming along the banks or on the bottom encloses gravel, sand, and even blocks of rock, which, when thaw comes, are lifted up and carried down the stream. In the rivers of Northern Russia and Siberia, which, flowing from south to north, have the ice thawed in their higher courses before it breaks up farther down, much disaster is sometimes caused by the piling up of the ice, and then by the bursting of the impeded river through the temporary ice-barrier. In another way, ice sometimes vastly increases the destructive power of small streams, where avalanches (p. 534) or an advancing glacier cross a valley and pond back its drainage. The valley of the Dranse, in Switzerland, has several times suffered from this cause. In 1818, the glacier-barrier extended across the valley for more than half a mile, with a breadth of 600 and a height of 400 feet. The waters above the ice-dam accumulated into a lake containing 800,000,000 cubic feet. By a tunnel driven through the ice, about two-fifths of the water were drawn off, when the dam, weakened by the enlargement of the tunnel, burst, carrying havoc into the lower part of the valley and the plain of the Rhône near Martigny. Fifty lives were lost, and 500 houses and chalets with several bridges were destroyed.[2]

The amount of sediment borne downwards by a river is not necessarily determined by the carrying power of the current. The swiftest streams are not always the muddiest. The proportion of sediment is partly dependent upon the hardness or softness of the rocks of the channel, the number of tributaries, the nature and slope of the ground forming the drainage-basin, the amount and distribution of the rainfall, the size of the glaciers (where such exist) at the sources of the river, the chemical composition of the water, and probably other causes. A rainfall spread with some uniformity throughout the year may not sensibly darken the rivers with mud, but the same amount of fall crowded into a few days or weeks may be the means of sweeping a vast amount of earth into the

[1] The extent to which heavy rains can alter the usual characters of rivers is forcibly exemplified in Sir T. Dick Lauder's 'The Morayshire Floods.' In the year 1829 the rivers of that region rose 10, 18, and in one case even 50 feet above their common summer level, producing almost incredible havoc. See also G. A. Koch, "Ueber Murbrüche in Tyrol," *Jahrb. Geol. Reichsanst.* xxv. (1875), p. 97.

[2] Bonney's 'Alpine Regions,' p. 185.

rivers, and sending them down in a greatly discoloured state to the sea. Thus the rivers of India, swollen during the rainy season (sometimes by a rainfall of 25 inches in 40 hours, as at the time of the destructive landslip at Naini Tal in September 1880, at other times by an even heavier downpour), become rolling currents of mud.[1]

The amount of mineral matter transported by rivers can be estimated by examining their waters at different periods and places, and determining their solid contents. A complete analysis should take into account what is chemically dissolved, what is mechanically suspended, and what is driven or pushed along the bottom. We have already dealt with the chemically dissolved ingredients. In determinations of the mechanically mixed constituents of river-water, it is most advantageous to obtain the proportion first by weight, and then from its average specific gravity to estimate its bulk as an ingredient in the water. According to experiments made upon the water of the Rhône at Lyons, in 1844, the proportion of earthy matter held in suspension was by weight $\frac{1}{17000}$. Earlier in the century the results of similar experiments at Arles gave $\frac{1}{7000}$ as the proportion when the river was low, $\frac{1}{250}$ during floods, and $\frac{1}{2000}$ in the mean state of the river. The greatest recorded quantity is $\frac{1}{48}$ by weight, which was found "when the river was two-thirds up, with a mean velocity of probably about 8 feet per second."[2] A. Guérard, who has more recently made observations at the mouth of this river, estimates the total annual discharge of sediment to amount to 23,540,000 cubic yards, or $\frac{1}{2188}$ of the volume of the water.[3] Lombardini gives $\frac{1}{300}$ as the proportion by volume of the sediment in the water of the Po. In the Vistula, according to Spittell, the proportion by volume reaches a maximum of $\frac{1}{48}$.[4] The Rhine, according to Hartsoeker, contains $\frac{1}{100}$ by volume as it passes through Holland, while at Bonn the experiments of L. Horner gave a proportion of only $\frac{1}{18000}$ by volume.[5] Stiefensand found that, after a sudden flooding, the water of the Rhine at Uerdingen contained $\frac{1}{1282}$ by weight. Bischof measured the quantity of sediment in the same river at Bonn during a turbid state of the water, and found the proportion to be $\frac{1}{4878}$ by weight; while at another time, after several weeks of continuous dry weather, and when the water had become clear and blue, he detected only $\frac{1}{57800}$.[6] In the Meuse, according to the experiments of Chandellon, the maximum of sediment in suspension in the month of December 1849 was $\frac{1}{2100}$, the minimum $\frac{1}{71420}$, and the mean $\frac{1}{10000}$.[7] In the Elbe, at Hamburg, the proportion of mineral matter in suspension and solution has been found by experiment to average about $\frac{1}{7400}$. The Danube, at Vienna, yielded to Bischof about $\frac{1}{4200}$ of suspended and dissolved matter.[8] The

[1] In his journeys through equatorial Africa, Livingstone came upon rivers which appear usually to consist more of sand than of water. He describes the Zingesi as "a sand-rivulet in flood, 60 or 70 yards wide, and waist deep. Like all these sand-rivers, it is for the most part dry; but, by digging down a few feet, water is to be found which is percolating along the bed on a stratum of clay. In trying to ford it," he remarks, "I felt thousands of particles of coarse sand striking my legs, which gave me the idea that the amount of matter removed by every freshet must be very great. . . . These sand-rivers remove vast masses of disintegrated rock before it is fine enough to form soil. In most rivers where much wearing is going on, a person diving to the bottom may hear literally thousands of stones knocking against each other."

[2] Surell, 'Mémoire sur l'Amélioration des Embouchures du Rhône.' Humphreys and Abbot, 'Report upon the Physics and Hydraulics of the Mississippi,' 1861, p. 147.

[3] *Min. Proc. Inst. Civ. Engin.* lxxxii. (1884-85), p. 309.

[4] *Ibid.* p. 148.

[5] *Edin. New Phil. Journ.* xviii. p. 102.

[6] 'Chemical Geology,' i. p. 122.

[7] *Annales des Travaux publics de Belgique*, ix. p. 204.

[8] *Op. cit.* i. p. 130. More recent observations by Sir Charles Hartley show that the

Durance has ordinarily a maximum of 30 grammes of sediment to one litre of water, or $\frac{1}{33}$ by weight. In exceptional floods it rises to 100 grammes per litre of water, or $\frac{1}{10}$ by weight. In extreme low water the proportion may sink to about $\frac{1}{1000}$; the average for nine years from 1867 to 1875 was about $\frac{1}{560}$.[1] The Garonne is estimated to contain perhaps $\frac{1}{100}$.[2] In the Avon, which falls into the Severn, the mean amount of suspended mud is estimated at $\frac{1}{376}$.[3] The observations of Mr. Everest upon the water of the Ganges show that, during the four months of flood in that river, the proportion of earthy matter is $\frac{1}{428}$ by weight, or $\frac{1}{856}$ by volume; and that the mean average for the year is $\frac{1}{510}$ by weight, or $\frac{1}{1021}$ by volume.[4] According to Mr. Login, the waters of the Irrawaddy contain $\frac{1}{1700}$ by weight of sediment during floods, and $\frac{1}{5725}$ during a low state of the river.[5] In the Yangtse the proportion of sediment by weight is estimated by Mr. H. B. Guppy at $\frac{1}{2188}$.[6] The amount in the water of the River Plate is computed to be $\frac{1}{7752}$ by weight.[7] The proportion of solid matter carried in suspension in the Nile was in May 1875 estimated to amount to 4772 parts in every 100,000 parts of water.[8]

With regard to the amount of coarser and heavier sediment pushed along the bottom of a river by the downward current, it is more difficult to obtain accurate measurements. But it must sometimes constitute a large proportion of the total bulk of solid material discharged into the sea. In the case of the Rhône, for example, it is concluded by M. Guérard that the quantity of sand rolled along the bed of this river into the Mediterranean in the course of a year is much greater than the lighter matter held in suspension in the water, and that "when the river, on approaching the sea, is no longer confined by embankments, the greater part of its alluvium is rolled along its bed." In flood-time it is not uncommon for whole banks of sand to travel bodily down the river.[9]

As already pointed out (p. 491), changes in the quantity and nature of the salts held in chemical solution in river-water affect the capacity of the streams for the transport of mineral matter in suspension, so that the same river may vary in this respect from one part of its course to another according to the chemical composition of the water of its tributaries. But probably these variations are on the whole trifling in amount, and far below the result attained when the river-water first reaches the salt water of the sea. As the mean of many observations carried on continuously at different parts of the Mississippi for months together, Humphreys and Abbot, the engineers charged with the investigation, found that the average proportion of sediment contained in the water of this river is $\frac{1}{1500}$ by weight or $\frac{1}{2900}$ by volume.[10] But besides the matter held in suspension, they observed that a large amount of coarse detritus is constantly being pushed along the bottom of the river. They estimated that this moving stratum carries every year into the Gulf of Mexico about 750,000,000 cubic feet of sand, earth and gravel. Their observations led them to conclude that the annual discharge of water by the Mississippi is 19,500,000,000,000 cubic feet, and consequently that the weight of mud annually carried into the sea by this river must reach the sum of

mean proportion of sediment by weight in the Danube water for ten years from 1862 to 1871 was $\frac{1}{3085}$, or (at specific gravity 1·9) $\frac{1}{5862}$ by volume.

1 G. Wilson, *Min. Proc. Inst. Civ. Engin.* li. (1877-78), p. 216.

2 Baumgarten, cited by Reclus, 'La Terre.'

3 T. Howard, *Brit. Assoc.* 1875, p. 179.

4 *Journ. Asiatic Society of Calcutta*, March 1832.

5 *Proc. Roy. Soc. Edin.* 1857.

6 *Nature*, xxii. p. 486. According to Dr. A. Woeikoff, this estimate is much under the truth: xxiii. p. 9. See also *op. cit.* p. 584.

7 G. Higgin, *Nature*, xix. p. 555.

8 Dr. Letheby, *2nd Egyptian Irrigation Report.*

9 *Min. Proc. Inst. Civ. Engin.* lxxxii. (1884-85), p. 309.

10 'Report,' p. 148. The specific gravity of the silt of the Mississippi is given as 1·9.

812,500,000,000 pounds. Taking the total annual contributions of earthy matter, whether in suspension or moving along the bottom, they found them to equal a prism 268 feet in height with a base of one square mile.

The value of these data to the geologist consists mainly in the fact that they furnish him with materials for an approximate measurement of the rate at which the surface of the land is lowered by subaerial waste. This subject is discussed at p. 586.

2. *Excavating Power.*—It was a prominent part of the teaching of Hutton and Playfair, that rivers have excavated the channels in which they flow. Experience in all parts of the world has confirmed this doctrine. The mechanical erosive work of running water depends for its rate and character upon (*a*) the friction of the detritus driven by the current against the sides and bottom of a watercourse, modified by (*b*) the varying declivity and the geological structure of the ground.

(*a*) Driven downward by the descending water of a river, the loose grains and stones are rubbed against each other, as well as upon the rocky bed, until they are reduced to fine sand and mud, and the sides and bottom of the channel are smoothed, widened and deepened. The familiar effect of running water upon fragments of rock, in reducing them to rounded pebbles, is expressed by the common epithet "water-worn." A stream which descends from high rocky ground may be compared to a grinding mill; large boulders and angular blocks of rock, disengaged by frosts, springs and general atmospheric waste, fall into its upper end; fine sand and silt are discharged into the sea.

In the series of experiments already referred to (p. 487), Professor Daubrée made fragments of granite and quartz to slide over each other in a hollow cylinder partially filled with water, and rotating on its axis with a mean velocity of 0·80 to 1 metre in a second. He found that after the first 25 kilometres (about 15½ English miles) the angular fragments of granite had lost $\frac{4}{10}$ of their weight, while in the same distance fragments already well rounded had not lost more than $\frac{1}{100}$ to $\frac{1}{400}$. The fragments rounded by this journey of 25 kilometres in a cylinder could not be distinguished either in form or in general aspect from the natural detritus of a river-bed. A second product of these experiments was an extremely fine impalpable mud, which remained suspended in the water several days after the cessation of the movement. During the production of this fine sediment, the water, even though cold, was found in a day or two to have acted chemically upon the granite fragments. After a journey of 160 kilometres, 3 kilogrammes (about 6½ lb. avoirdupois) yielded 3·3 grammes (about 50 grains) of soluble salts, consisting chiefly of silicate of potash. A third product was an extremely fine angular sand consisting almost wholly of quartz, with scarcely any felspar, nearly the whole of the latter mineral having passed into the state of clay. The sand-grains, as they are continually pushed onward over each other upon the bottom of a river, become rounded as the larger pebbles do. But a limit is placed to this attrition by the size and specific gravity of the grains.[1] As a rule, the smaller particles suffer proportionately less loss than the larger, since the friction on the bottom varies directly as the weight and therefore as the cube of the diameter, while the surface exposed to attrition varies as the square of the diameter. Mr. Sorby, in calling attention to this relation, remarks that a grain $\frac{1}{10}$ of an inch in diameter would be worn ten times as much as one $\frac{1}{100}$ of an inch in diameter, and a pebble 1 inch in diameter would be worn relatively more by being drifted a few hundred yards than a sand-grain $\frac{1}{100}$ of an inch in diameter would be by being drifted for a hundred miles.[2] So long as the particles are borne along in

[1] 'Géologie expérimentale,' p. 250 *et seq.*

[2] *Q. J. G. S.* xxxvi. p. 59.

suspension, they will not abrade each other, but remain angular. Professor Daubrée found that the milky tint of the Rhine at Strasburg in the months of July and August was due, not to mud, but to a fine angular sand (with grains about $\frac{1}{20}$ millimetre in diameter) which constitutes $\frac{2}{100000}$ of the total weight of water. Yet this sand had travelled in a rapidly flowing, tumultuous river from the Swiss mountains, and had been tossed over waterfalls and rapids in its journey. He ascertained also that sand-grains with a mean diameter of $\frac{1}{10}$ mm. will float in feebly agitated water; so that all sand of finer grain must remain angular. The same observer noticed that sand composed of grains with a mean diameter of $\frac{1}{2}$ mm., and carried along by water moving at a rate of 1 metre per second, is rounded, and loses about $\frac{1}{10000}$ of its weight in every kilometre travelled.[1]

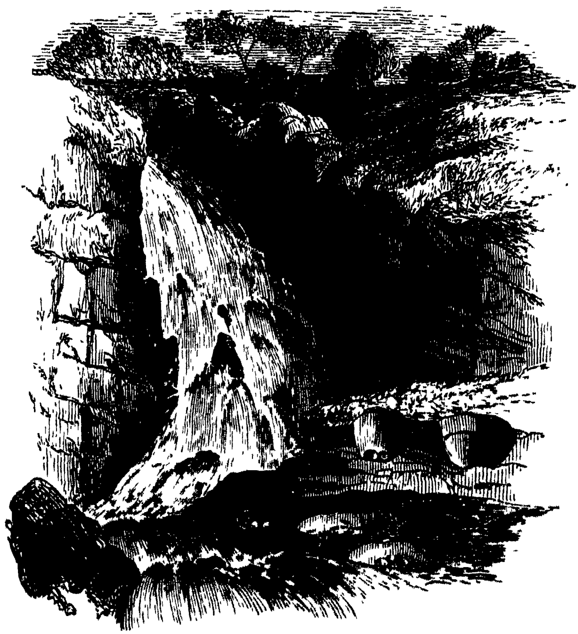

Fig. 116.—Rocky River-channel with old Pot-holes.

The effects of abrasion upon the loose materials on a river-bed are but a minor part of the erosive work performed by the stream. A layer of débris, only the upper portion of which is pushed onward by the normal current, will protect the solid rock of the river-channel which it covers, but it is apt to be swept away from time to time by violent floods. Sand, gravel and boulders, in those parts of a river-channel where the current is strong enough to keep them moving along, rub down the rocky bottom over which they are driven. As the shape and declivity of the channel vary constantly from point to point, with, at the same time, frequent changes in the nature of the rocks, this erosive action is liable to continual modifications. It advances most briskly in the numerous

[1] 'Géologie expérimentale,' pp. 256, 258.

hollows and grooves along which chiefly these loose materials travel. Wherever an eddy occurs in which gravel is kept in gyration, erosion is much increased. The stones, in their movement, excavate a hole in the channel, while, as they themselves are reduced to sand and mud, or are swept out by the force of the current, their places are taken by fresh stones brought down by the stream (Fig. 116). Such *pot-holes*, as they are termed, vary in size from mere cup-like depressions to huge caldrons or pools. As they often coalesce, by the giving way of the intervening walls between two or more of them, they materially increase the deepening of the river-bed.

That a river erodes its channel by means of its transported sediment and not by the mere friction of the water, is sometimes admirably illustrated in the course of streams filtered by one or more lakes. As the Rhône escapes from the Lake of Geneva, it sweeps with a swift clear current over ledges of rock that have not yet been very deeply eroded. The Niagara supplies a still more impressive example. Issuing from Lake Erie, and flowing through a level country for a few miles, it approaches its falls by a series of rapids. The water leaves the lake with hardly any appreciable sediment, and has too brief a journey in which to gather it, before beginning to rush down the rocky channel towards the cataract. The sight of the vast body of clear water, leaping and shooting over the sheets of limestone in the rapids, is in some respects quite as striking a scene as the great falls. To a geologist it is specially instructive; for he can observe that, notwithstanding the tremendous rush of water which has been rolling over them for so many centuries, these rocks have been comparatively little abraded. The smoothed and striated surface left by the ice-sheet of the Glacial period can be traced upon them almost to the water's edge, and the flat ledges at the rapids are merely a prolongation of the ice-worn surface which passes under the banks of drift on either side. The river has hardly eroded more than a mere superficial skin of rock here since it began to flow over the glaciated limestone.

Similar evidence is offered by the St. Lawrence. This majestic river leaves Lake Ontario as pure as the waters of the lake itself. The ice-worn hummocks of gneiss at the Thousand Islands still retain their characteristic smoothed and polished surface down to and beneath the surface of the current. In descending the river, I was astonished to observe that the famous rapids of the St. Lawrence are actually hemmed in by islets and steep banks of boulder-clay, and not of solid rock. So little obvious erosion does the current perform, even in its tumultuous billowy descent, that a raw scar of clay betokening a recent slip is hardly to be seen. The banks are so grassed over, or even covered with trees, as to prove how long they have remained undisturbed in their present condition. That very considerable local destruction of these clay-islands, however, has been caused by floating ice will be alluded to farther on.

Mere volume and rapidity of current, therefore, will not cause much erosion of the channel of a stream unless sediment be present in the water. A succession of lakes, by detaining the sediment, must necessarily enfeeble the direct excavating power of a river. On the other hand, by the disintegrating action of the atmosphere, and by the operations of springs and frosts, loose detritus as well as portions of the river-banks are continually being launched into the currents, which, as they roll along, are thus supplied with fresh materials for erosion.

(*b*) Besides the obvious relation between the angle of slope of a river-bed and the scouring force of the river, a dominant influence, in the gradual excavation of a river-channel, is exercised by the lithological

nature and geological structure of the rocks through which the stream flows. This influence is manifested in the form of the channel, the angle of declivity of its banks, and in the details of its erosion. On a small but instructive scale these phenomena are revealed in the operations of brooks. Thus, one of the most characteristic features of streams, whether large or small, is the tendency to wind in serpentine curves when the angle of declivity is low, and the general surface of the country tolerably level. This peculiarity may be observed in every stream which traverses a flat alluvial plain.

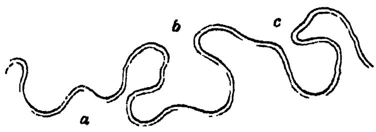

Fig. 117.—Meandering course of a Brook.

Some slight weakness in one of its banks enables the current to cut away a portion of the bank at that point. By degrees a concavity is formed round which the upper water sweeps with increased velocity, while under-currents tend to carry sediment across to the opposite side. The outer bank is accordingly worn away, while the inner or concave side of the bend is not attacked, but is even protected by a deposit of sand or gravel.[1] Thus, bending alternately from one side to the other, the stream is led to describe a most sinuous course across the plain. By this process, however, while the course is greatly lengthened, the velocity proportionately diminishes, until, before quitting the plain, the stream may become a lazy, creeping current, in England commonly bordered with sedges and willows. A stream may eventually cut through the neck of land between two loops, as at *a*, *b*, and *c*, in Fig. 117, and thus for a while shorten its channel. Instances of this nature may frequently be observed in streams flowing through alluvial land. The old deserted loops[2] are converted, first into lakes, and by degrees into stagnant pools or bogs, until finally, by growth of vegetation and infilling of sediment by rain and wind, they become dry ground.

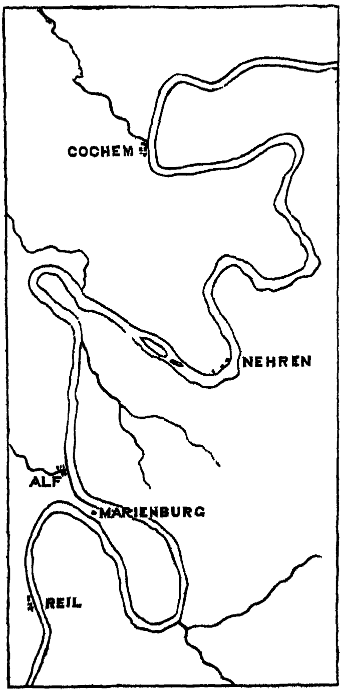

Fig. 118.—Windings of the Gorge of the Moselle above Cochem.

Although most frequent in soft alluvial plains, meandering water-

[1] J. Thomson, *Proc. Roy. Soc.* xxv. (1876), p. 5. According to observations and deductions by Prof. M. Jefferson, the width of the belt of meanders of any given stream is eighteen times the mean width of the stream at the place. *National Geograph. Mag.* xiii. (1902), p. 373.

[2] "Aigues-mortes," or dead waters. See p. 517, *note* 2.

courses may also be eroded in solid rock if the original form of the surface was tolerably flat. The windings of the gorges of the Moselle (Fig. 118) and Rhine through the table-land between Trèves, Mainz and the Siebengebirge form a notable illustration.

Abrupt changes in the geological structure or lithological character of the rocks of a river-channel may give rise to waterfalls. In many cases, this feature of river-scenery has originated in lines of escarpment over which the water at first found its way, or in the same geological arrangement of hard and soft rocks by which the escarpments themselves have been produced. The occurrence of horizontal, tolerably compact strata, traversed by marked lines of joint, and resting upon softer beds, presents a structure well adapted for showing the part played by waterfalls in river-erosion. The waterfall acts with special potency against the softer underlying materials at its base. These are hollowed out, and, as the foundations of the superincumbent more solid rocks are destroyed, slices of the latter from time to time fall off into the boiling whirlpool, where they are reduced to fragments and carried down the stream. Thus the waterfall cuts its way backward up the stream, and as it advances it prolongs the excavation of the ravine into which it descends. The student will frequently observe, in the recession of waterfalls and consequent erosion of ravines, the important part taken by lines of joint in the rocks. These lines have often determined the direction of the ravine, and the vertical walls on either side depend for their precipitousness mainly upon these divisional planes in the rock.

The gorge of the Niagara affords a magnificent and remarkably simple illustration of these features of river-action. At its lower end, where it enters the wide plain that extends to Lake Ontario, there stretches away, on either side of the river, a line of cliff and steep wooded bank, formed by the escarpment of the massive Niagara limestone. Back from this line of cliff, through which it issues into the lacustrine plain, the gorge of the river extends for about 7 miles, with a width of from 200 to 400 yards, and a depth of from 200 to 300 feet. At the upper end lie the world-renowned falls. The whole of this great ravine has unquestionably been cut out by the recession of the falls. When the river first began to flow, it may have found the escarpment running across its course, and may then have begun the excavation of its gorge. More probably, however, the escarpment and waterfall began to arise simultaneously, and from the same geological structure. As the former grew in height, it receded from its starting-point. The river-ravine likewise crept backward, but at a more rapid rate, and the result has been that while at present the cliff, worn down by atmospheric disintegration, stands at Queenstown, the ravine dug by the river extends 7 miles farther inland. The waterfall will continue to cut its way back as long as the structure of the gorge continues as it is now—thick beds of limestone resting horizontally upon soft shales (Fig. 119). The softer strata at the base are undermined, and slice after slice is cut off from

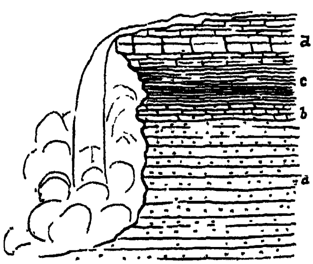


Fig. 119.—Section at the Horse-shoe Falls, Niagara.

*a*, Medina Sandstone and Shale, 120 feet; *b*, Clinton Limestone and Shale, 35 feet; *c*, Niagara Shale, 60 feet; *d*, Niagara Limestone, 55 feet.

the cliff over which the cataract pours. The parallel walls of this great gorge owe their direction and mural character to parallel joints of the strata. The lesser or American fall (A in Fig. 120) enters by the side of the ravine and falls over its lateral wall. The larger or Canadian (Horse-shoe) fall (C) occupies the head of the ravine, and owes its form to the intersection of two sets of joints. Bakewell, from historical notices and the testimony of old residents, inferred that the rate of recession of the falls is three feet in a year. Lyell concluded that "the average of one foot a year would be a much more probable conjecture," and estimated the length of time

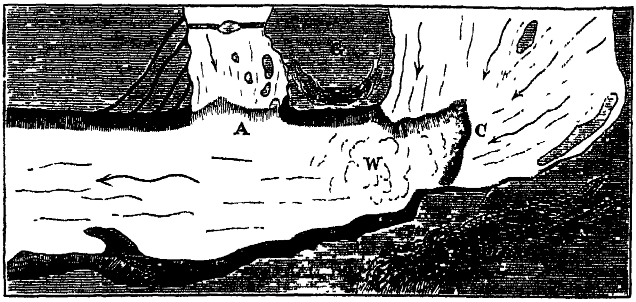


Fig. 120.—Plan of the Ravine of Niagara at the Falls.
A, American Fall; C, Canadian Fall; W, Whirlpool; G, Goat Island; D, Bank of Drift resting on ice-worn sheets of Limestone.

required for the excavation of the whole Niagara ravine at 35,000 years.[1] A commission appointed to survey the falls and to ascertain the rate of recession reported (1890) that since 1742, when the first survey was made, the total mean recession of the Horse-shoe falls has been 104 feet 6 inches. The maximum recession at one point is 270 feet. The mean recession of the American falls is 30 feet 6 inches. The length of the crest has increased from 2260 to 3010 feet by the washing away of the embankment. The total area of recession of the American falls is 32,900 square feet, and that of the Horse-shoe falls 275,400 feet. But the rate of waste has been ascertained not to be uniform, there being intervals of slower and more rapid retreat, during which the form of the precipice at the falls is continually changing. Professor J. W. Spencer, from a review of all the evidence that he and others have been able to gather respecting the geological structure of the district, has traced the successive stages in the excavation of the ravine and the connection of the erosion with the history of the great glacial lakes which once overspread that region. He shows the importance of the movement of elevation which for a long period has been transforming the topography (*ante*, p. 387), and which in the Niagara districts he takes for the purposes of computation to be 15 inches in a century. He consequently arrives at the estimate of about 30,000 years as the age of the Niagara ravine.

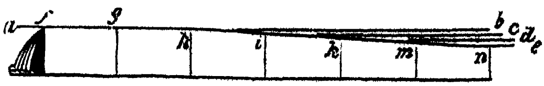


Fig. 121.—Section to illustrate the lowering of Lake Erie by the recession of Niagara Falls.

It was long ago pointed out that if the structure of the gorge continued the same from the falls to Lake Erie, the recession of the falls would eventually tap the lake,

[1] Lyell, 'Travels in North America,' i. p. 32; ii. p. 93. 'Principles,' i. p. 358. Compare Lesley's 'Coal and its Topography' (1856), p. 169. On recent changes at the Falls, see Marcou, *Bull. Soc. Géol. France* (2), xxii. p. 290; and also *ante*, p. 459.

and reduce its surface to the level of the bottom of the ravine. Successive stages in this retreat of the falls are shown in Fig. 121, by the letters *f* to *n*, and in the consequent lowering of the lake by the letters *a*, *b* to *c*. It was believed, however, that a slight observable inclination of the strata would carry the soft underlying shale out of possible reach of the fall, and that in this way the lowering of the lake would be indefinitely retarded.[1] But the discovery of the slow uplift of the land with a generally southerly tilt has given a wholly new aspect to the problem, showing that if this movement should continue as at present the drainage now carried by the Niagara will at no very distant geological period find its way southward into the Mississippi.[2]

The Falls of St. Anthony on the Mississippi show, according to Winchell, a rate of recession varying from 3·49 to 6·73 feet per annum, the whole recession since the discovery of the falls in 1680 to the present time being 906 feet.[3] The upper or Rock Island rapids of the Mississippi consist of a succession of rock-barriers called "chains," which, with a breadth of only a fraction of a mile, pass across the channel, and are separated by pools or stretches of slack water. The lower or Des Moines rapids, about 11 miles long, are more uniform, having a descent of nearly two feet per mile.[4]

A waterfall may occasionally be observed to have been produced by the existence of a harder and more resisting band or barrier of rock crossing

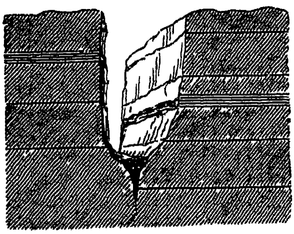

Fig. 122.—River-gorge in line of Fault.

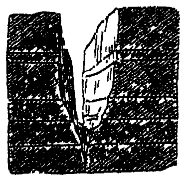

Fig. 123.—River-gorge in Fissured Strata.

the course of the stream, as, for instance, where the rocks have been cut by an intrusive dyke or mass of basalt, or where, as in the case of the Rhine at Schaffhausen, and possibly in that of the Niagara, the stream has been diverted out of its ancient course by glacial or other deposits, so as to be forced to carve out a new channel and rejoin its older one by a fall.[5] In these and all other cases, the removal of the harder mass destroys the waterfall, which, after passing into a series of rapids, is finally lost in the general abrasion of the river-channel.

The resemblance of a deep, narrow river-gorge to a rent opened in the ground by subterranean agency, has often led to a mistaken belief that such marked superficial features could only have arisen from actual violent dislocation. Even where something is conceded to the river, there is a natural tendency to assume that there must have been a line of fault and displacement as in Fig. 122, or at least a line of crack, and

[1] Lyell's 'Principles,' i. p. 362.

[2] See the papers cited *ante*, p. 387, *note* 2, and more particularly Professor Spencer's in *Amer. Journ. Sci.* xlviii. (1894), p. 455.

[3] *Q. J. G. S.* xxxiv. p. 899.

[4] F. Leverett, *Journ. Géol.* vii. (1899), p. 1. The history of the lower rapids is shown by this observer to belong partly to the Glacial period. He estimates that they have excavated a depth of nearly 100 feet of rock.

[5] Würtenberger, *Neues Jahrb.* 1871, p. 582.

consequent weakness (Fig. 123). But the existence of an actual fracture is not necessary for the formation of a ravine of the first magnitude.

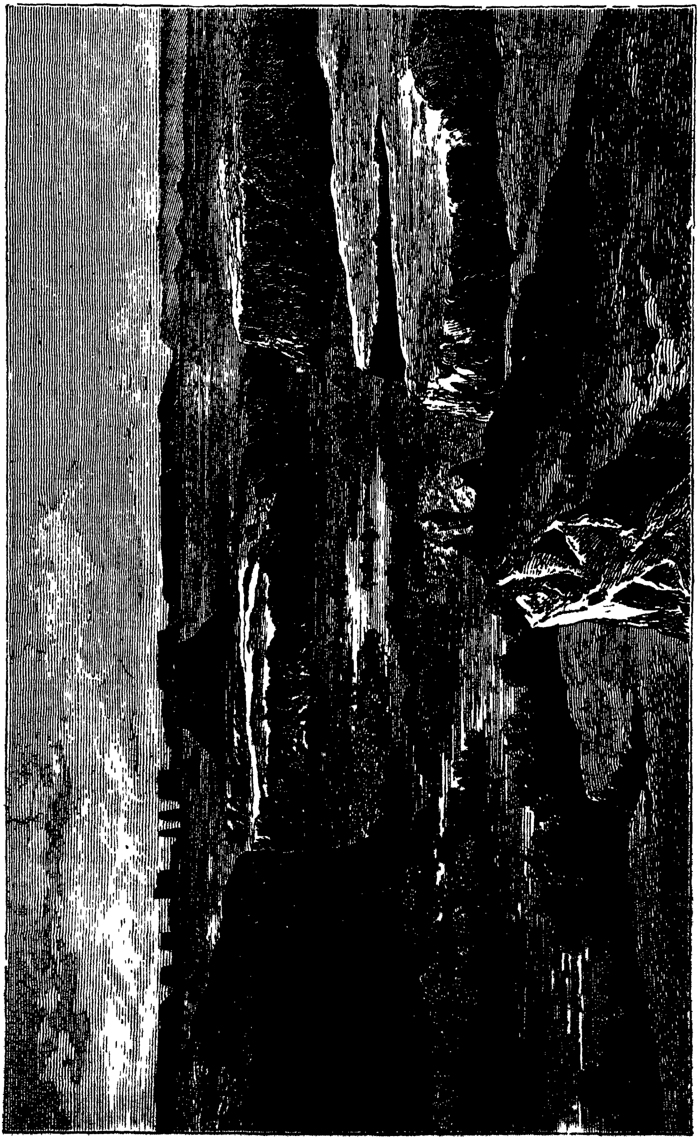

Fig. 124.—View of the erosion of the San Juan. Colorado Basin (Newberry).

The gorge of the Niagara, for example, has not been determined by any dislocation. Still more impressive proof of the same fact is furnished by the most marvellous river-gorges in the world—those of the Colorado region in North America. The rivers there flow in ravines thousands of feet deep and hundreds of miles long, through vast table-lands of

nearly horizontal strata. The Grand Cañon (ravine) of the Colorado river is 300 miles long, and in some places more than 6000 feet in depth. In many instances there are two cañons, the upper being several miles wide, with vast lines of cliff-walls and a broad plain between them, in which runs the second cañon as another deep gorge with the river winding over its bottom. The country is hardly to be crossed except by birds, so profoundly has it been trenched by these numerous gorges. Yet the whole of this excavation has been effected by the erosive action of the streams themselves.[1] Some idea of the vastness of the erosion of these plateaux may be formed from Fig. 124, the Frontispiece to this volume, and the illustrations in Book VII.

In the excavation of a ravine, whether by the recession of a waterfall or of a series of rapids, the action of the river is more effective than that of the atmospheric agents. The sides of the ravine consequently retain their vertical character, which, where they coincide with lines of joint, is further preserved by the way in which atmospheric weathering acts along the joints. But where, from the nature of the ground or of the climate, the denuding action of rain, frost and general weathering is more rapid than that of the river, a wider and opener valley is hollowed out, through which the river flows, carrying away the materials washed into it from the surrounding slopes by rain and brooks.

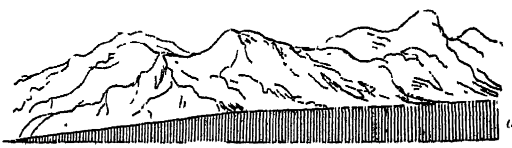


Fig. 125.—Section of part of a River-channel (*B.*).

3. *Reproductive Power.*—Every body of water which, when in motion, carries along sediment, drops it when at rest. The moment a current has its rapidity checked, it is deprived of some of its carrying power, and begins to lose hold upon its sediment, which tends more and more to sink and halt on the bottom the slower the motion of the water. In Fig. 125 the river in flowing from *a* to *b* has a less angle of declivity and a smaller transporting power, and will therefore have a greater tendency to throw down sediment, than in descending the steeper gradient from *b* to *c*. Again, as has been pointed out (*ante*, p. 491), variations in the proportions of chemically dissolved substances affect the precipitation of suspended sediment.

In the course of every brook and river, there are frequent checks to the current. If these are examined, they will usually be found to be each marked by a more or less conspicuous deposit of sediment. We may notice seven different situations in which stream-deposits or *alluvium* may be accumulated.

(*a*) At the foot of Mountain Slopes.—When a runnel or torrent

[1] For descriptions and figures of this remarkable region, see Ives and Newberry, 'Explorations of the Colorado River of the West,' 1861; J. W. Powell, 'Exploration of the Colorado River of the West and its Tributaries,' 1875; Captain Dutton, 'Tertiary History of the Grand Cañon of the Colorado'; *Monograph II., U. S. Geological Survey*, 4to, 1882; and *postea*, Book VII.

descends a deep declivity it tears down the soil and rocks, cutting a gash out of the side of the mountain (Fig. 126). On reaching the more

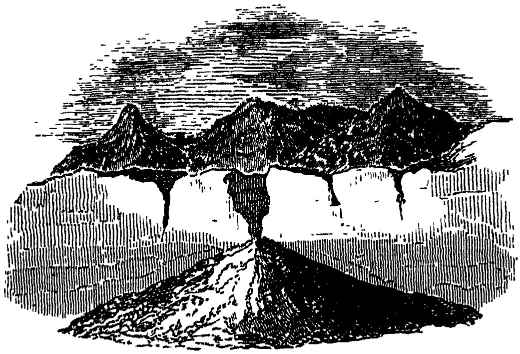

Fig. 126.—Tributary torrent sending a cone of detritus into a valley (B.).

level ground at the base of the slope, the water, abruptly checked in its velocity, at once drops its coarser sediment, which gathers in a fan-shaped pile or cone ("*cone de déjection*"; "*Murbrüche*"[1]), with the apex pointing up the water-course. Huge accumulations of boulders and shingle may thus be seen at the foot of such torrents,—the water flowing through them, often in several channels, which re-unite in the plain beyond. From the deposits of small streams, every gradation of size may be traced up to huge fans many miles in diameter and several hundred feet thick,

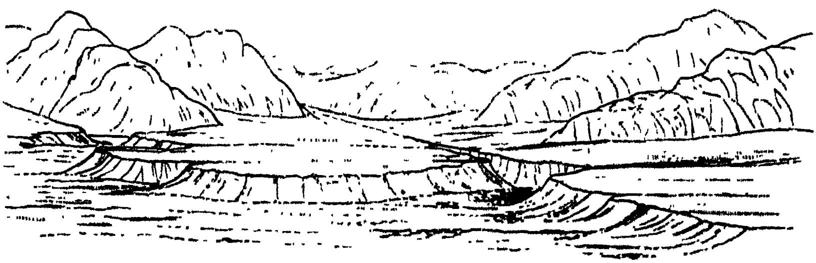

Fig. 127.—Fans of Alluvium. Madison River, Montana.

such as occur in the upper basin of the Indus[2] and on the flanks of the Rocky Mountains,[3] as well as other ranges in North America (Fig. 127).[4]

[1] G. A. Koch, *Jahrb. Geol. Reichsanst.* xxv. (1875), p. 97, describes the debacles of the Tyrol. Consult also the work of Surell and Cézanne cited on p. 482.

[2] On the alluvial deposits of this region, see Drew, *Q. J. G. S.* xxix. p. 441; also his 'Jummoo and Kashmere Territories,' 1875.

[3] See Dutton's 'High Plateaux of Utah.' Hayden's *Reports of the U. S. Geological and Geographical Surveys of the Territories.*

[4] In the great inland basin of North America, which includes the arid tracts of Great Salt Lake and other saline waters, the depth of accumulated detritus must amount in many places to several thousand feet. See on this subject I. C. Russell, *Geol. Mag.* 1889; and Gilbert's essay on lake-shores in the *5th Annual Report of the U. S. Geol. Surv.*

The level of the valleys in the Tyrol has been sensibly raised within historic times by the detritus swept into them from the surrounding mountains. Old churches and other buildings are half-buried in the accumulated sediment.[1]

(*b*) In River-beds.—The deposition of alluvium on river-beds is characteristically shown by the accumulation of sand or shingle at the concave side of each sharp bend of a river-course. While the main upper current is making a more rapid sweep round the opposite bank, under-currents pass across to the inner side of the curve and drop their freight of loose detritus, which, when laid bare in dry weather, forms the familiar sand-bank or shingle-beach (p. 499). Again, when a river, well supplied with sediment, leaves mountainous ground where its course has been rapid, and enters a region of level plain, it begins to drop its burden on the channel, which is thereby heightened, till it may actually rise above the level of the surrounding plains (Fig. 128).

Fig. 128.—Section of a River-plain, showing heightening of channel by deposits of sediment (*B*.).

This tendency is displayed by the Adige, Reno and Brenta, which, descending from the Alps well supplied with detritus, debouch on the plains of the Po.[2] The Po itself has been quoted as an instance of a river continuing to heighten its bed, while man in self-defence heightens its embankments, until the surface of the river becomes higher than the plains on either side. It has been shown by Lombardini, however, that the bed of this river has undergone very little change for centuries; that only here and there does the mean height of the water rise above the level of the plains, being generally considerably below it, and that even in a high flood the surface of the river is scarcely ten feet above the pavement in front of the Palace at Ferrara.[3] The Po and its tributaries have been carefully embanked, so that much of the sediment of the rivers, instead of accumulating on the plains of Lombardy, as it naturally would do, is carried out into the Adriatic. Hence, partly, no doubt, the remarkably rapid rate of growth of the delta of the Po. But in such cases, man needs all his skill and labour to keep the banks secure. Even with his utmost efforts, a river will now and then break through, sweeping down the barrier which it has itself made, as well as any additional embankments constructed by him, and carrying its flood far and wide over the plain. Left to itself, the river would incessantly shift its course, until in turn every part of the plain had been again and again traversed. It is indeed in this way that a great alluvial plain is gradually levelled and heightened. The most stupendous example of the gradual heightening of a plain by river deposits, and of the devastation caused by the bursting of the artificial barriers raised to control the stream, is that of the Hoang Ho or Yellow River. So frequently has this river changed its course across the great

[1] G. A. Koch, *Jahrb. Geol. Reichsanst.* xxv. (1875), p. 123.

[2] It is in the north of Italy that the struggle between man and nature has been most persistently waged. See Lombardini, in *Ann. des Ponts-et-Chaussées*, 1847; E. Nicolis, "Sugli antichi corsi del fiume Adige," *Bol. Soc. Geol. Ital.* xvii. (1898), pp. 7-76: Beardmore's 'Tables,' p. 172. The bed of the Yang-tse-Kiang has been raised in places far above the level of the surrounding country by embanking. E. L. Oxenham, *Journ. Geog. Soc.* xlv. (1875), p. 182.

[3] Between Mantua and Modena the Po is said to have raised its bed more than 5½ metres since the fifteenth century. Dausse, *Bull. Soc. Géol. France*, iii. (3me sér.), p. 137.

eastern plain, and so appalling has been the consequent devastation, that it has received the name of "China's sorrow." A great inundation took place in the autumn of 1887, when hundreds of villages were submerged and more than a million human beings were drowned. Breaking down its frail embankment, the stream poured through the breach, which was some 1200 yards wide, and spread out over a width of 30 miles in a current ten to twenty feet deep in the middle.

(*c*) On River-banks and Flood-plains.—As is partly implied in the action described in the foregoing paragraph, alluvium is laid down on the level tracts or flood-plain over which a river spreads in flood. It consists usually of fine silt, mud, earth or sand; though close to the channel, it may be partly made up of coarser materials. When a flooded river overflows, the portions of water which spread out on the plains, by losing velocity, and consequently power of transport, are compelled to let fall more or less of their mud and sand. If the plains happen to be covered with wood, bushes, scrub or tall grass, the vegetation acts the part of a sieve, and filters the muddy water, which may rejoin the main stream comparatively clear. The height of the plain is thus increased by every flood, until, partly from this cause and partly, in the case of a

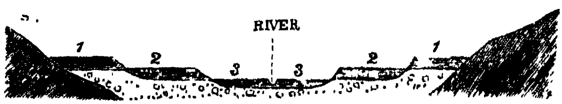

Fig. 129.—Section of River-terraces.

rapid stream, from the erosion of the channel, the plain can no longer be overspread by the river. As the channel is more and more deepened, the river continues, as before, to be liable, from inequalities in the material of its banks, sometimes of the most trifling kind, and from the behaviour of water flowing in irregular channels, to wind from side to side in wide curves and loops, and cuts into its old alluvium, making eventually a newer plain at a lower level. Prolonged erosion carries the channel to a still lower level, where the stream can attack the later alluvial deposit, and form a still lower and newer one. The river comes by this means to be fringed with a series of terraces (Fig. 129), the surface of each of which represents a former flood-level of the stream.

In Britain, it is common to find three such terraces, but sometimes as many as six or seven or even more may occur. On the Seine and other rivers of the north of France, there is a marked terrace at a height of 12 to 17 metres above the present water-level. In North America, the river-terraces exist on so grand a scale that the geologists of that country have named one of the later periods of geological history, during which those deposits were formed, the *Terrace Epoch* (Fig. 129). The modern alluvium of the Mississippi, from the mouth of the Ohio to the Gulf of Mexico, covers an area of 19,450 miles, and has a breadth of from 25 to 75 miles and a depth of from 25 to 40 feet. The old alluvium of the Amazon likewise forms extensive lines of cliff for hundreds of miles, beneath which a newer platform of detritus is being formed.[1]

[1] The stages of terrace-making in the *régime* of a great river are well brought out in the case of the Amazon. C. B. Brown, *Q. J. G. S.* xxxv. p. 763. The subject of the origin

A recent elaborate study of the terraces in the valleys of the Isser, Moselle, Rhine and Rhône has been made by Colonel De Lamothe.[1] He believes that he can recognise in each of these valleys six platforms or terraces of deposit comprised within a height of 200 metres above the present streams, and at approximately the same distance from each other. He thinks that they are to be explained by simultaneous oscillations of level, which brought about alternate erosion and filling up of the valley bottoms. In the Moselle the heights of these old levels of the river are given as follows: 1st, from 15 to 20 metres; 2nd, 30 metres; 3rd, from 45 to 56 metres; 4th, 100 metres; 5th, from 130 to 150 metres; 6th, about 200 metres. The terraces of the Rhine in the immediate neighbourhood of Bâle are given as occurring at the following levels above the present stream: 1st, traces of a terrace from 15 to 20 metres, passing into the next above; 2nd, at 31 metres; 3rd, from 56 to 60 metres; 4th, from 99 to 101 metres; 5th, from 130 to 150 metres; 6th, traces of a higher level of perhaps from 200 to 230 metres. It will be observed that the limits assigned have tolerably wide limits of

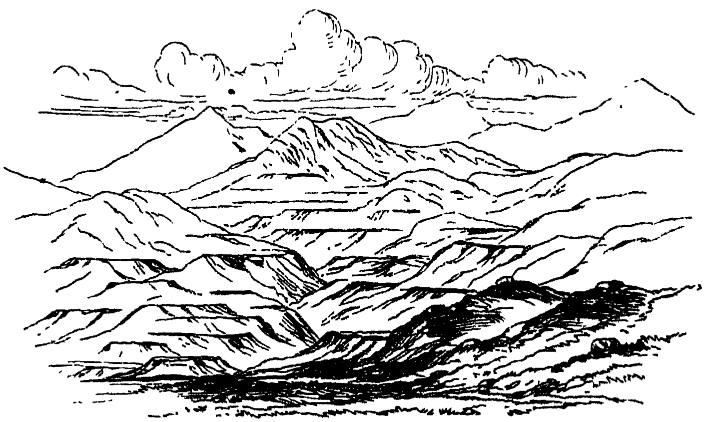

Fig. 130.—Old Terraces on the left bank of the Yellowstone River, above the first Cañon. Montana.

variation, and it may be open to question how far such a generalisation as that of Colonel De Lamothe is well founded. There can be no doubt, however, that a succession of river-terraces is a clearly established fact for all parts of the world, in what direction soever its interpretation is to be sought.

In considering the probable history of the river-terraces in connection with the evolution of the topography of a country, the first point to be ascertained is whether these terraces have been entirely cut out of older detrital deposits. If such has been the case, it is obvious that the valley must be of older date than even the oldest of the terraces. In Fig. 129, for instance, the succession of river-terraces only marks a late series of fluviatile operations long subsequent to the excavation of the valley, and the filling of it up with the drift deposits on which these terraces lie. The next question is the determination of the number, continuity and relative levels of the successive terraces in the various rivers in a wide

of river-terraces is ably treated by the late H. Miller of the Geological Survey in *Proc. Roy. Phys. Soc. Edin.* 1883, p. 263.

[1] *Bull. Soc. Géol. France*, 4me sér. i. (1901), pp. 297-388; and an earlier paper by the same author, *op. cit.* xxvii. (1899), p. 257; Kilian on the 'surcreusement des vallées alpines,' *op. cit.* xxviii. (1900), p. 1004.

region, so as to ascertain how far any satisfactory parallelism can be established between the terrace systems of different valleys. From this basis of accurate observation it will be practicable to consider whether there is so close a parallelism as to make it improbable that it should be due merely to the independent working of the rivers themselves, and to indicate the co-operation of some general cause affecting all the drainage of the whole region examined. In seeking for such a cause the observer will first inquire whether the succession of fluviatile changes points to any probable former meteorological conditions, such for instance as oscillations of rainfall, advance or retreat of glaciers. In this search the detailed later geological history of the ground will need to be carefully worked out. Should no satisfactory evidence be obtainable to warrant a reference of the terrace system to variations of a climatological kind, it will be proper to consider how far the phenomena can be explained by elevation of the land. An uplift by increasing the height and slope of the ground will augment the scour of the rivers; and if the movement should be intermittent, with long pauses of rest and shorter intervals of rapid rise, the effects on the drainage could not fail to be marked. Each interval of upward movement would lead to increased erosion of the river-channels; and during the long stationary rests, or if a subsidence of the land took place, the streams might often in places reach a base level of erosion and be there mainly occupied in spreading out alluvium. In applying this hypothetical explanation to any region the geologist would require to be in possession of a detailed and accurate series of levellings, so as to be able to fix the precise height of each terrace in valley after valley, to note its variation in level between the higher and lower parts of its course, to ascertain whether in the case of the maritime part of a country a connection could be traced between the successive river-terraces of the interior and any strand-lines or raised marine beaches along the coast, and generally to determine the axis or centre of elevation and its probable amount.[1]

(*d*) In Lakes.—When a river enters a lake or inland sea its current is checked, and its sediment begins to spread in fan-shape over the bottom (*c* in Fig. 131). Every tributary stream brings in its contribution of detritus. In this way, a series of shoals is pushed out into the lake (Fig. 132 and p. 522). This phenomenon may frequently be instructively observed from a height overlooking a small lake among mountains. At the mouth of each torrent or brook lies a little tongue of its alluvium (a true *delta*), through which the streamlet winds in one

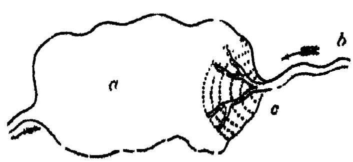

Fig. 131.—Streamlet (*b*) entering a small lake (*a*), and depositing a fan of sediment (*c*).

[1] This subject still needs much detailed study and comparison of drainage systems. There can be little doubt that both in Europe and in North America the rivers at a comparatively recent geological period were larger than they are at present. Professor Dana connected the river-terraces of the Eastern States of North America with stages in the elevation of the axis of the continent.

or more branches, before mingling its waters with those of the lake. Two streams entering from opposite sides (as at *c*, *d*, Fig. 132) may join their alluvia and divide a lake into two, like the once united lakes of Thun and Brienz at Interlaken. Or, by the advance of the alluvial deposits, the lake may be finally filled up altogether, as has happened in innumerable cases in all mountainous countries (Fig. 133).

The rapidity of the infilling is sometimes not a little remarkable. Since the year 1714, the Kander is said to have thrown into the Lake of Thun a delta measuring 230 acres, now partly woodland, partly meadow and marsh. The Aar, at its entrance into the Lake of Brienz, has deposited a delta 3500 to 4000 feet broad, formed of detritus which at the mouth of the river has an outward slope of 30°, that gradually falls to the nearly level lake-floor. In twenty-seven years after its rectification the Reuss had laid down in the Lake of Lucerne a delta estimated to contain upwards of 141 million of cubic feet of sediment, which is equivalent to a discharge of 19,350 cubic feet in a day, or nearly 7,000,000 cubic feet in a year.[1]

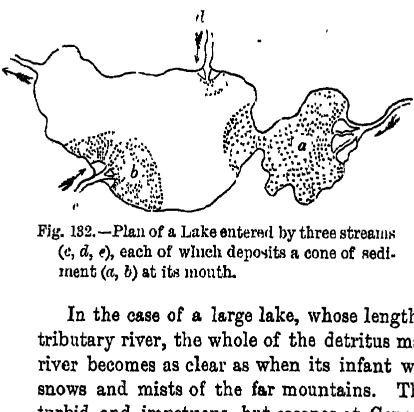


Fig. 132.—Plan of a Lake entered by three streams (*c*, *d*, *e*), each of which deposits a cone of sediment (*a*, *b*) at its mouth.

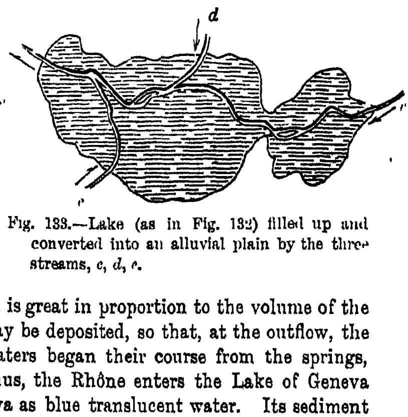


Fig. 133.—Lake (as in Fig. 132) filled up and converted into an alluvial plain by the three streams, *c*, *d*, *e*.

In the case of a large lake, whose length is great in proportion to the volume of the tributary river, the whole of the detritus may be deposited, so that, at the outflow, the river becomes as clear as when its infant waters began their course from the springs, snows and mists of the far mountains. Thus, the Rhône enters the Lake of Geneva turbid and impetuous, but escapes at Geneva as blue translucent water. Its sediment is laid down on the floor of the lake, and chiefly at the upper end, as an important delta which quite rivals that of a great river in the sea. Hence, lakes act as filters or sieves to intercept the sediment which is travelling in the rivers from the high grounds to the sea (p. 522).[2]

(*e*) Estuarine Deposits; Bars and Lagoon-barriers.—If we take a broad view of terrestrial degradation, we must admit that the deposit of any sediment on the land is only temporary; the inevitable destination of all detrital material is the floor of the sea. Where a gently flowing river comes within the influence of the alternate rise and fall of the tides, a new set of conditions is established in regard to the disposal of the sediment. During the flow of the tide in the Severn, for example, the suspended mud is carried up the estuary, and sometimes far up its tributaries. For two-thirds of the ebb, though the surface-water is running out rapidly, the bottom water is practically at rest: only during the remaining third of the ebb does the bottom-water flow outwards and with sufficient

[1] A. Heim, *Jahrb. Schweizer Alpenklubs*, 1879.

[2] Consult the suggestive essay by G. K. Gilbert on the topographic features of lake-shores, *5th Ann. Rep. U. S. Geol. Surv.* 1885, p. 75.

velocity to scour the channel. But this lasts for so short a time that it hardly removes as much mud or sand as has been laid down during flood and the earlier part of ebb tide. Hence the sediment is in a state of continual oscillation upward and downward in the estuary. At the lower end, some portion of it is continually being swept out to sea. At the upper end, fresh material of similar kind is being supplied by the river. But, between these two limits, the same sediment may be kept in suspension or may be alternately deposited or removed for many weeks or months before it finally escapes to sea and is spread out on the bottom. To this cause, doubtless, the remarkable turbidity of many estuaries is to be attributed.[1]

Where a river, with a considerable velocity of current, enters the sea, its mouth is commonly obstructed by a bar of gravel, sand or mud. The formation of this barrier results from the conflict between the river and the ocean. The muddy fresh water floats on the heavier salt water, its current is lessened, and it can no longer push along the mass of detritus at the bottom, which therefore accumulates and tends to form a bar. Moreover, as already mentioned (p. 491), though fresh water can for a long time retain fine mud in suspension, this sediment is rapidly thrown down when the fresh is mixed with saline water. Hence, apart from the necessary loss of transporting power by the checking of the current at the river-mouth, the mere mingling of a river with the sea must of itself be a cause of the deposit of sediment. Moreover, in many cases the sea itself piles up great part of the sand and gravel of the bar. Heavy river-floods push the bar farther to sea, or even temporarily destroy it; storms from the sea, on the other hand, drive it farther up the stream.

But besides the bars at the mouths of rivers, a much more extensive accumulation of alluvium from the land is found in the form of a long bank, which accumulates in front of a low shore, and sometimes stretches along a coast-line intermittently for hundreds of miles. This bank or barrier consists of sand, silt, or even gravel, which is continually transported along the coast by the prevalent current. Owing to the shallowness of the water the waves begin to break at some distance from the beach, and the agitation which they cause checks the onward drifting of the sediment, which consequently accumulates in a bank that is gradually increased in height, until eventually by the aid of occasional storms it is raised above the line of high water. Though the barrier retains this position, its materials along the seaward slope are continually being pushed onward along the coast, while fresh supplies of sediment arrive to make good the waste. Inside the barrier lies a long strip or lagoon of calm water, which at first is of course a portion of the sea. But by degrees, as the barrier grows, the direct connection of the lagoon with the sea may be cut off, and the water inside may in the end become fresh. The detritus brought into it from the land slowly fills it up, until it may pass into the condition of a morass or peat-moss, and eventually into a plain

[1] See an interesting paper by Professor Sollas, *Q. J. Geol. Soc* xxxix. (1883), p. 611, and authorities there cited.

on which, though its surface may be below the level of high water, trees will grow. If, however, owing to any cause, the supply of sediment to the barriers outside should fail, the waves will begin to attack the accumulation, and when it is breached the sea will at high-water inundate the woodland inside. As already remarked (p. 388), it was no doubt by some such succession of changes that many of the so-called "submerged forests" of Western Europe were produced. By the formation of coast-barriers the seaward portion of the drainage of a country may be seriously affected. Rivers are sometimes made to flow parallel to the shore-line for long distances before their waters can find an exit to the sea. Here and there, though there may be no visible outlet, the water of the lagoon is kept from overflowing by soaking through the porous barrier and so reaching the beach outside. Elevation of the land on such lagoon-fringed coasts gives rise to a maritime border of flat alluvium. Portions of the "raised beaches" of Britain which have had this origin contain peat-filled hollows with sheets of marl full of lacustrine shells.

Some of these facts in the economy of rivers have been well studied at the mouths of the Mississippi. At the south-west pass, the bar is equal in bulk to a solid mass one mile square and 490 feet thick, and advances at the rate of 338 feet each year. It is formed where the river-water begins to ascend over the heavier salt water of the gulf, and consists mainly of the sediment that is pushed along the bed of the river. A singular feature of the Mississippi bars is the formation upon them of "mud-lumps." These are masses of tough clay, varying in size from mere protuberances like tree-trunks, up to islands several acres in extent. They rise suddenly, and attain heights of from 3 to 10, sometimes even 18 feet above the sea-level. Salt springs emitting inflammable gas rise upon them. After the lapse of a considerable time, the springs cease to give off gas, and the lumps are worn away by the currents of the river and the gulf. The origin of these excrescences has been attributed to the generation of carburetted hydrogen by the decomposing vegetable matter in the sediment underlying the tenacious clay of the bars.[1]

Conspicuous examples of the formation of detrital bars may occasionally be observed at the mouths of narrow estuaries, as at *e* in Fig. 134. A constant struggle takes place in such situations between the tidal currents and waves which tend to heap up the bar and block the entrance to the estuary, and the scour of the river and ebb-tide which endeavours to keep the passage open.

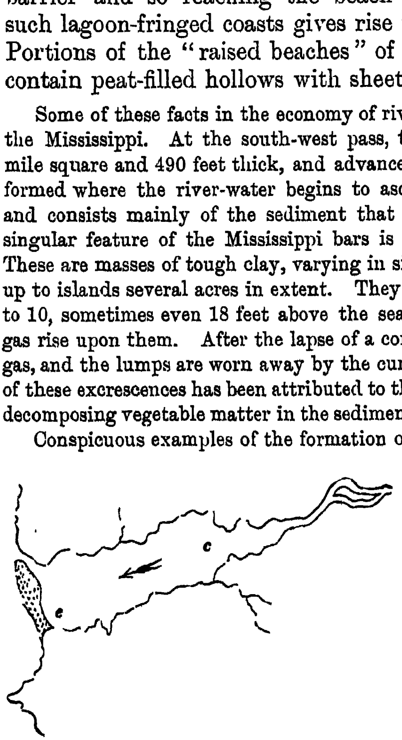

Fig. 134.—Shingle and Sand-spit (*e*) at the mouth of an estuary (*c*), entered by a river, and opening upon an exposed rocky coast-line (*B*.).

On a coast-line such as that of Western Europe, subject both to powerful tidal action and to strong gales of wind, many interesting illustrations may be studied of the struggle between the rivers and the sea, as to the disposal of the sediment borne from the land. De la Beche described an example from the coast of South Wales, where two streams, the Towey and Nedd (*a* and *b*, Fig. 135), enter Swansea Bay, bearing with them a considerable amount of sandy and muddy sediment. The fine mud is carried by the ebb-tide (*t t t*) into the sheltered bay between Swansea (*c*) and the Mumble Rocks (*e*), but is partly swept

[1] Humphreys and Abbot, 'Report on Mississippi River,' 1861, p. 452.

round this headland into the Bristol Channel. The coarser sandy sediment, more rapidly thrown down, is stirred up and driven shorewards by the breakers caused by the prevalent west and south-west winds (*w*). The sandy flats thereby formed are partly uncovered at low water, and being then dried by the wind, supply it with the sand which it blows inland to form the lines of sand-dunes (*ff*).[1]

Of lagoon barriers many examples may be observed on maps of Europe, India and North America. Instructive illustrations may often be found on a small scale where

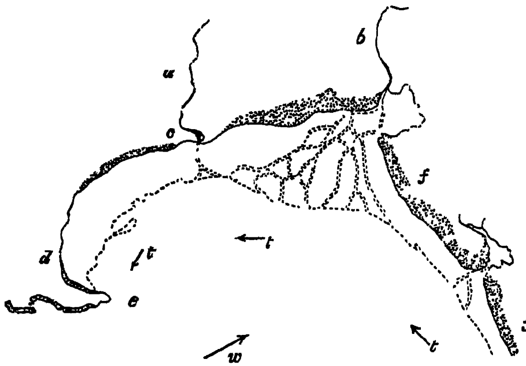


Fig. 135.—Action of rivers, tides and winds in Swansea Bay (*P.*).

the main features of the structure are well displayed. Thus at Start Bay, on the coast of Devon (Fig. 136), the rocks of the country, which consist of slates (*e*) generally overspread with a coating of their own decayed substance (*d*), slip under the water of a freshwater lagoon (*c*) which is separated from the sea (*a*) by a barrier (*b*) of detritus. The lagoons of the shores of the Mediterranean,[2] and the Kurische and Frische Haf in the Baltic, near Dantzic, are familiar examples. The southern coast of Iceland is for many

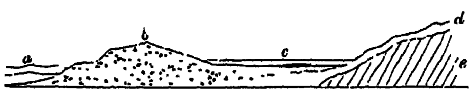


Fig. 136.—Section of Bar and Lagoon. Slapton Pool, Start Bay, Devon (*B.*).

leagues fringed with sand-bars formed from the sediment carried down by the glacier rivers from the great ice-fields.[3] A conspicuous series of these alluvial bars fronts the American mainland for many hundred miles round the Gulf of Mexico and the shores of Florida, Georgia and North Carolina (Fig. 137).[4] A space of several hundred miles on the east coast of India is similarly bordered. Élie de Beaumont, indeed, estimated that about a third of the whole of the coast-lines of the continents is fringed with such alluvial bars.[5]

[1] 'Geological Observer,' p. 88.

[2] For an account of these, see Ansted, *Min. Proc. Inst. Civ. Engin.* xxvii. (1869), p. 287.

[3] See Dr. Thoroddsen's map of Iceland, 1901, and his notes in *Geografisk Tidskrift*, vol. xii. (1893-94), part vii. p. 208.

[4] See Report by H. D. Rogers, *Brit. Assoc.* iii. p. 13. Some information regarding these features as displayed on the eastern coast of the United States will be found in a paper by J. F. Newson, *Journ. Geol.* vii. (1899), p. 445.

[5] 'Leçons de Géologie pratique,' i. p. 249. Some interesting examples of this kind of deposit are there described.

(*f*) Deltas in the Sea.[1]—The tendency of sediment to accumulate in a tongue of flat land when a river loses itself in a lake, is exhibited on a vaster scale where the great rivers of the continents enter the sea. It

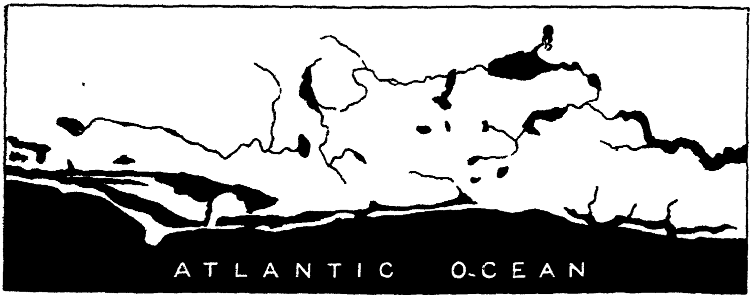


Fig. 137.—Plan of Coast-bars and Lagoons. Coast of Florida.

was to one of these maritime accumulations, that of the Nile, that the Greeks gave the name delta, from its resemblance to their letter Δ, with the apex pointing up the river, and the base fronting the sea (Fig. 138).

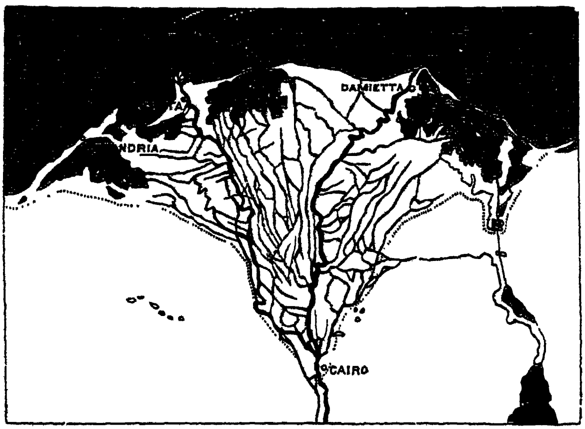


Fig. 138.—Map of the Delta of the Nile. The limits of the river alluvium are shown by the dotted lines.

This shape being the common one in all such alluvial deposits at river-mouths, the term delta has become their general designation. A delta consists of successive layers of detritus, brought down from the land and spread out at the mouth of a river, until they reach the surface, and then, partly by growth of vegetation and partly by flooding of the river, form a plain, of which the inner and higher portion comes eventually to be above the reach of floods. Large quantities of drift-wood are often carried down, and bodies of animals are swept off to be buried in the delta, or even to be floated out to sea. Hence, in deposits formed at

[1] H. Credner discusses this subject in a paper entitled "Die Deltas," *Peterm. Mitth.* Ergänzungsband xii. (1878).

the mouths of rivers, we may always expect to find terrestrial organic remains.

A delta does not necessarily form at every river-mouth, even where there is plenty of sediment. In particular, where the coast-line on either side is lofty, and the water deep, or where the coast is swept by powerful tidal currents, there is no delta.[1] In some cases, too, the sediment spreads out over the sea-bottom without being allowed by the sea to build itself up into land, as happens at the mouths of some of the rivers in the north-west of France. Considerable influence may be exerted by tides and currents in arresting or facilitating the spread of sediment over the sea-floor. The deltas of the Rhône, Nile, Tiber and Danube have been formed in tideless or nearly tideless seas.[2]

When a river enters upon the delta portion of its course, it assumes a new character. In the previous parts of its journey it is augmented by tributaries; but now it begins to split up into branches, which wind to and fro through the flat alluvial land, often coalescing and thus enclosing insular spaces of all dimensions. The feeble current, no longer able to bear along all its weight of sediment, allows much of it to sink to the bottom and to gather over the tracts which are from time to time submerged. Hence many of the channels are choked up, while others are opened out in the plain, to be in turn abandoned; and thus the river restlessly shifts its channels. The seaward ends of at least the main channels grow outwards by the constant accumulation of detritus pushed into the sea, unless this growth chances to be checked by any marine current sweeping past the delta.

The typical delta of the Nile (Fig. 138) affords an excellent illustration of the main features of delta-building. Of the seven ancient mouths of this river only two now remain. As shown on the map, many threads of water wind across the plain, and after depositing their silt find their way into wide shallow lakes or lagoons, which are separated from the sea by low alluvial barriers. Everywhere beneath the fluviatile deposits of the delta there lies a thick mass of yellowish ferruginous sand and gravel. On this substratum the river has piled up a depth of about 30 metres of fine alluvial clay. To this plain it is estimated that an annual layer of fresh material is added amounting to about 24,400,000 cubic metres, while the proportion of silt carried past the delta and out to sea is computed at 36,600,000 cubic metres. This vast tribute of mineral matter does not, however, go to increase the extent of the delta seaward, for a powerful marine current sweeps past the coast and carries the sediment eastward beyond the most easterly mouth of the river. Hence the delta has reached a period in its history where it is still increased in height by an annual deposit of silt, but cannot extend horizontally save where the ground on either side of it is so low as to be covered during the inundation. The silt delivered into the Mediterranean by the Rosetta and Damietta branches is eventually thrown down along the coast of the El Arich desert. Part of it, however, is arrested by the great jetty which has been run out from Port Said, and so rapid is the growth of land there that the coast has advanced about 600 metres since the construction of that piece of engineering.[3]

[1] Consult Admiral Spratt's memoir, 'An Investigation of the Effect of the prevailing Wave Influence on the Nile's Deposit,' folio, London, 1859.

[2] For a discussion on non-tidal rivers, see *Min. Proc. Inst. Civ. Engin.* lxxxii. (1885), pp. 2-68, where information is given about the Tiber and some other rivers.

[3] R. Fortau, "Sur les Dépôts Nilotiques," *B. S. G. F.* xxvi. (1898), p. 545. Élie de Beaumont on the Nile delta, 'Leçons de Géologie pratique,' i. (1845), pp. 405-492.

Other characteristic aspects of delta-formation where no antagonistic marine curre interferes are well displayed by the delta of the river Mississippi (Fig. 139). The ar of this vast expanse of alluvium is given at 12,300 square miles, advancing at the rate 262 feet yearly into the Gulf of Mexico at a point which is now 220 miles from the he of the delta.[1] On a smaller scale the rivers of Europe furnish many excellent illustratio of delta-growth. Thus the alluvial accumulations of the Rhine, Meuse, Sambre, Schel and other rivers have formed the wide maritime plain of the Netherlands.[2] T Rhône, which has deposited an important delta in the Mediterranean Sea, is co puted to furnish every year (by the Petit Rhône) about four millions of cubic metres

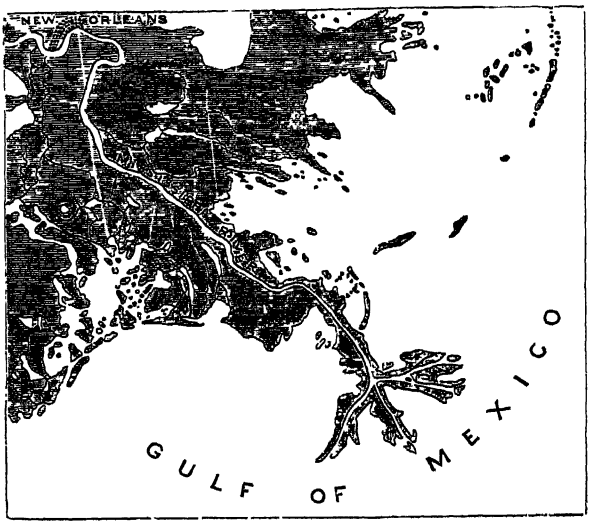


Fig. 139.—Map of Delta of Mississippi.

sediment to the shores.[3] The upper reaches of the Adriatic Sea are being so rapi shallowed and filled up by the Po, Adige and other streams, that Ravenna, origina built in a lagoon like Venice, is now 4 miles from the sea; and the port of Adria, well known in ancient times as to have given its name to the Adriatic, is now 14 mi inland, while on other parts of that coast-line the breadth of land gained within t last 1800 years has been as much as 20 miles. Borings for water near Venice to a de of 572 feet have disclosed a succession of nearly horizontal clays, sands and lignitifer beds. Marine shells (*Cardium*, &c.) occur in the sandy layers; the lignites and lign ferous clays contain land vegetation and terrestrial shells (*Succinea*, *Pupa*, *Helix*), t

[1] Humphreys and Abbot, *op. cit.*; see also C. Hartley, *Min. Proc. Inst. Civ. Eng* xl. p. 185; W. Upham, "Growth of Mississippi Delta," *Amer. Geol.* xxx. (1902), p. 1 The tide has a mean rise of 15 inches every 24 hours at the Mississippi mouths.

[2] Man has contributed in a considerable degree to the changes of this part of Eur during historic times, and his influence continues to be shown. He has reclaimed w tracts once frequently inundated, he has kept out the sea by dykes, and he has schemes turning the Zuider Zee into cultivable land. See "The Reclamation of the Zuider Z (with map), *Geog. Journ.* i. (1893), p. 234; W. H. Wheeler, *Nature*, lxv. (1902), p. 275

[3] For this delta and its lagoons, see the paper by Ansted, quoted *ante*, p. 513. Rec 'Géographie universelle,' tome ii. (France), chaps. ii. and iii.; and A. Guérard, *Min. P Inst. Civ. Engin.* lxxxii. (1884-85), p. 305.

whole succession of deposits indicating an alternation of marine and terrestrial or fresh-water conditions.[1] On the opposite side of the Italian peninsula, great additions have been made to the coast-line within the historical period. It is computed that the Tuscan rivers lay down as much as 12 million cubic yards of sediment every year within the marshes of the Maremma. The "yellow" Tiber, as it was aptly termed by the Romans, owes its colour to the abundance of the sediment which it carries to sea. It has long been adding to the coast-line around its mouth at the rate of from 12 to 13 feet per annum. The ancient harbour of Ostia is now consequently more than 3 miles inland. Its ruins have been partially excavated, but every high flood of the river leaves

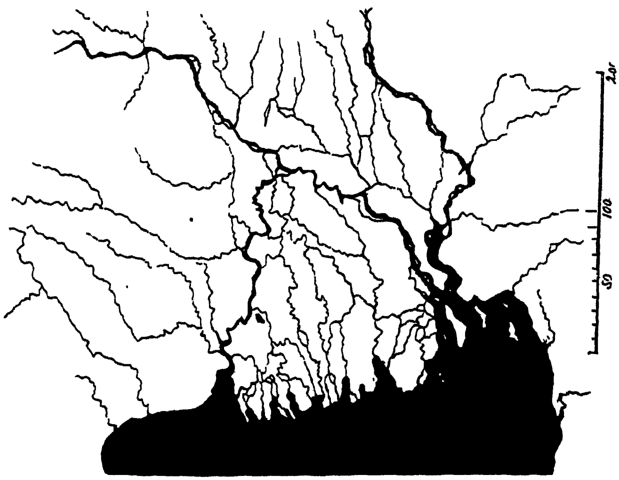


Fig. 140.—Delta of the Ganges and Brahmaputra (with scale of miles).

a deposit of mud on the streets and on the floors of the uncovered houses. Hence it would seem that the Tiber has not only advanced its coast-line but has raised its bed on the plains, by the deposit of alluvium, so that it now overflows places which, 2000 years ago, could not have been so frequently under water.[2] In the Black Sea, a great delta is rapidly growing at the mouths of the Danube. At the Kilia outlets the water is shallowing so fast that the lines of soundings of 6 feet and 30 feet are advancing into the sea at the rate of between 300 and 400 feet per annum.[3] The typical delta of the Nile has a seaward border 180 miles in length, the distance from which to the apex of the plain where the river bifurcates is 90 miles.[4] The united delta of the Ganges and

[1] Élie de Beaumont, 'Leçons de Géologie pratique,' i. p. 323. *Geol. Mag.* ix. (1872), p. 486.

[2] See an interesting article by Charles Martins on the Aigues-mortes (*i.e.* dead waters or disused river-channels), in *Revue des Deux Mondes*, 1874, p. 780. I accompanied the distinguished French geologist on the occasion of his visit to Ostia in the spring of 1873, and was much struck with the proofs of the rapidity of deposit in favourable situations. In the article just cited, and in another in *Comptes rend.* lxxviii. p. 1748, some valuable information is given regarding the progress of the delta of the Rhône in the Mediterranean. Interesting historical data as to geological changes at the mouths of the Rhine, Meuse, Elbe, Po, Rhône and other European rivers, as well as of the Nile, will be found in Élie de Beaumont's 'Leçons de Géologie pratique,' i. p. 253.

[3] Hartley, *Min. Proc. Inst. Civ. Engin.* xxxvii. p. 216.

[4] For a detailed study of the Nile delta in its geological aspects, see an essay by Dr. J. Jankó, *Mittheil. Jahrb. Kön. Ungarischen Geol. Anst.* viii. (1890), p. 236.

Brahmaputra (Fig. 140) covers a space of between 50,000 and 60,000 square miles, and has been bored through to a depth of 481 feet, the whole mass of deposits consisting of fine sands and clays, with occasional pebble-beds, a bed of peat and remains of trees, but with no trace of any marine organism.[1]

(*g*) Sea-borne Sediment.—Although more properly to be noticed under the section on the Sea, the final course of the materials worn by rains and rivers from the surface of the land may be referred to here. By far the larger part of these materials sinks to the bottom close to the land. It is only the fine mud carried in suspension in the water which is carried out to sea. In none of the numerous soundings and dredgings in the Gulf of Mexico has Mississippi mud been obtained from the bottom more than 100 miles eastward from the mouth of the river.[2] The soundings taken by the *Challenger*, however, brought up land-derived detritus from depths of 1500 fathoms—200 miles or more from the nearest shores (p. 581). The sea fronting the Amazon is sometimes discoloured for 300 miles by the mud of that river.

## § 4. Lakes.

Depressions filled with water on the surface of the land, and known as Lakes, occur abundantly in the northern parts of both hemispheres, and more sparingly, but often of large size, in warmer latitudes.[3] For the most part, they do not belong to the normal system of erosion in which running water is the prime agent, and to which the excavation of valleys and ravines must be attributed. On the contrary, they are exceptional to that system, for the constant tendency of running water is to fill them up. Their origin, therefore, must be sought among some of the other geological processes. (See Book VII.)

[1] For a full account of the alluvium of the Indo-Gangetic plain, see Medlicott and Blanford's 'Geology of India,' chap. xvii., and authorities there cited ; also a more recent paper by Mr. Medlicott, *Records Geol. Surv. India*, 1881, p. 220.

[2] A. Agassiz, *Amer. Acad.* xii. (1882), p. 108.

[3] A useful compendium of information on the subject of lakes is supplied in F. A. Forel's 'Handbuch der Seenkunde,' Stuttgart, Engelhorn, 1900. English lakes are discussed by H. R. Mill, *Geog. Journ.* vi. (1895), pp. 46-73, 135-166 ; J. Marr, *Q. J. G. S.* li. (1895), p. 35 ; lii. (1896), p. 12. Scottish lakes by J. Murray, J. P. Pullar, B. N. Peach, and J. Horne, *Scottish Geograph. Mag.* xvi. (1900), pp. 309-353 ; xvii. (1901), pp. 273-296. The lakes of France by A. Delebecque, in his large and well-illustrated work, 'Les Lacs Français,' Paris, 1898. The lakes of Switzerland by Forel in the work above referred to; in his monograph, 'Le Leman,' Lausanne, 2 vols. 1892, 1895—a valuable essay on the *régime* of a typical lake ; and in many papers in the *Compt. rend.* from 1875 onwards. The lakes of Italy by O. Marinelli, *Revist. Geograf. Ital.* i. (1894), ii. (1895) ; G. de Agostini, 'Il Lago d'Orta,' Turin, 1897 ; *Bol. Soc. Geog. Ital.* 1898, fasc. ii. and ix. ; 1899, fasc. iii. ; *Atti 3° Congr. Geog. Ital.* 1898 (gives a bibliography of the subject). The traces of large Pleistocene lakes in Southern Italy have been described by G. de Lorenzo, *Atti Accad. Sci.*, Naples, ix. (1898). The Balaton Lake (Plattensee), the largest sheet of water in Hungary, has been made the subject of an elaborate monograph by a Committee of the Hungarian Geographical Society, in which the physics, chemistry, geology, flora, fauna, archæology and ethnography of the area are described : 'Resultate der wissenschaftlichen Erforschung des Plattensees,' 3 vols. 4to, Vienna, 1897-98 and subsequent years.

Lakes are conveniently classed as fresh or salt. Those which possess an outlet contain in almost all cases fresh water; those which have none are usually salt.

1. **Fresh-water Lakes.**—In the northern parts of Europe and America, as first emphasised by Sir Andrew C. Ramsay, lakes are prodigiously abundant on ice-worn rock-surfaces, irrespective of dominant lines of drainage. They seem to be distributed as it were at random, being found now on the summits of ridges, now on the sides of hills, and now over broad plains. They lie for the most part in rock-basins, but many of them have barriers of detritus. Their connection with the operations of the Glacial period will be afterwards alluded to. In the mountainous regions of temperate and polar latitudes, lakes abound in valleys, and are connected with main drainage-lines. In North America [1] and in Equatorial Africa [2] vast sheets of fresh water occur in depressions of the land, and are rather inland seas than lakes.

Lakes may be classified according to the nature and origin of the basins in which they lie. (1) Some have been produced by irregular movements of the lithosphere, whereby hollows have been formed at the surface, by which the drainage is intercepted. Such movements may be connected with mountain-making or with slow distortion and fracture of the crust, like the uplift which is now gradually altering the topography of the Great Lakes of North America; or with sudden and rapid disturbances, as in earthquakes, when the ground is rent or thrown into undulations; or with the operations of volcanoes, like the crater-lakes of Italy, the Eifel, and Central France. (2) Other lakes have been formed as the result of erosion. Sometimes the material has been removed by solution, as in the meres of Cheshire that arise from the abstraction of rock-salt by underground water, or in the lakes of the Karst type, where the solution has affected limestones. In other cases the erosion has been of a mechanical kind, as where wind has scooped out hollows that become temporarily or permanently filled with water,[3] or where water falling over a cliff of ice or rock excavates a hollow in the rock below, or where land-ice grinds out a basin in a solid rock (*postea*, p. 552). (3) Still another class of lakes has arisen from the deposition of material in such a form as to arrest and retain sheets of

[1] Out of the voluminous literature which has gathered round the Great Lakes of North America the following writings may be cited here:—The papers by G. K. Gilbert and those of J. W. Spencer already quoted on p. 387; also J. W. Spencer, *Amer. Geol.* xiv. (1894), p. 289; xxi. (1898), p. 110; A. N. Winchell, *op. cit.* xix. (1897), p. 336.

[2] Among the papers devoted to the investigation of the Great African lakes are those by R. Sieger, *Jahresb. Verein Geograph. Universität, Wien*, xiii. (1887); *Globus*, lxii. 1892; *Q. J. G. S.* xlix. (1893), p. 579. A. Carson, *Q. J. G. S.* xlviii. (1892), p. 401; *Peterm. Mitt.* xxxviii. (1892), p. 250; xxxix. (1893), p. 47; *Proc. Roy. Geograph. Soc.* 1892, p. 827. J. E. S. Moore, *Proc. Roy. Soc.* lxii. (1898), p. 450; *Nature*, lviii. (1898), pp. 404; lix. pp. 152, 251; *Quart. Journ. Micro. Sci.* xli. pp. 159-180. These papers furnish biological evidence in favour of the lakes having once been connected with the sea. Captain Boileau and L. A. Wallace, *Geog. Journ.* xiii. (1899), p. 577.

[3] *Ante*, p. 437. As further examples, the dry lakes of Western Australia may be referred to. H. P. Woodward, *Geog. Mag.* 1897, p. 363.

water. Frequent illustrations of this operation are supplied by landslips, which when they are launched across valleys pond back the drainage above them. Similar effects are sometimes produced by rivers where they throw down barriers of detritus across tributary valleys. But the most impressive examples are probably those supplied by glaciers. Here and there the ice itself, advancing down a main valley, blocks up the mouth of a tributary, as the Aletsch glacier has done in the case of the Märjelen Sea. More frequently it is the moraines shed by the ice that have impeded the drainage, as in thousands of examples all over the northern hemisphere. The detritus left by the sheets of ice that once overspread so much of Northern Europe and North America had a most irregular surface, and many of its hollows on the retirement of the ice became and still remain water-filled lakes. The lagoons that lie inside the barriers of sand or gravel thrown up along a sea-coast sometimes become fresh-water lakes (*ante*, p. 511). The loops of water left isolated where a river has straightened its course (Aigues-mortes, p. 499) likewise form permanent lakes.[1]

The water of many lakes has been observed to rise above its normal level for a few minutes or for more than an hour, then to descend beneath that level, and to continue this vibration for some time. In the Lake of Geneva, where these movements, locally known there as *Seiches*, have long been noticed, the amplitude of the oscillation ranges up to a metre or even sometimes to two metres. These disturbances may sometimes be due to subterranean movements; but probably they are mainly the effect of atmospheric perturbations, and, in particular, of local storms with a vertical descending movement.[2]

The distribution of temperature in lakes is a question of considerable geological interest, as it affects climate and lacustrine faunas and floras. As far back as 1788, Count Morozzo made observations of the vertical range of temperature in the Lago d'Orta in Piedmont; and though, from the imperfect thermometers then available, his results have no precise value, they demonstrated the important fact that the water some distance down was colder than that of the surface. This observation has since been verified by much more exact determinations. It is now well known that in lakes of considerable depths, situated in regions where the winter temperature is low, a permanent mass of cold water lies at the bottom. The cold, heavy water of the surface in winter sinks down; and as the upper layers cannot be heated by the direct rays of the sun, save to a trifling and superficial extent, the temperature of the deep parts of these basins is kept permanently at little above that of the maximum density of fresh water (39° Fahr.; 3·89° C.).

At Loch Lomond in Scotland, which lies 25 feet above sea-level, with a depth of about 600 feet, and is in great measure surrounded with high hills, Christison found a

[1] See a good paper by Professor W. M. Davis, "On the Classification of Lake Basins," *Proc. Boston Soc. Nat. Hist.* xxi. (1882), p. 315.

[2] F. A. Forel, *Comptes rend.* lxxx. (1875), p. 107; lxxxiii. (1876), p. 712; lxxxvi. (1878), p. 1500; lxxxix. (1879), p. 859; *Assoc. Française*, 1879, p. 498. P. du Bois, *Comptes rend.* cxii. (1891), p. 122.

tolerably constant temperature of about 42° Fahr. in the lowest 100 feet of water.[1] More extended observations have since been made by Sir John Murray and the staff of the Scottish Marine Station in Lochs Ness, Oich, Morar and Shiel, as well as in some of the fjords and sounds of the west of Scotland, and the earlier deductions have been confirmed. The surface of Loch Morar in September 1887 was found to have a temperature of 57·8° Fahr., but at a depth of 160 fathoms the thermometer had fallen to 42·1°. The surface temperature of Loch Ness in the same month was 54°, but at 120 fathoms 42·1°.[2] Careful thermometric soundings have been carried on in the Italian lakes by Signor G. de Agostini. In the Lago d'Orta, where the early observations of Count Morozzo were made, he found that in September, while the temperature of the surface water ranged between 20° and 23·2° C., at a depth of 140 metres it was persistently 5·2° C. In February the temperature of the surface water was as low as 4·9° and the water at 140 metres was 4·8°—the winter temperature prevailing from top to bottom of the lake. In the Lago Maggiore, the September temperature of the superficial water is 22° C., that of the bottom water (at 350 metres) 5·7°. In the Lugano lake the numbers were 21·5° and (at 240 metres) 5·3°; in that of Como 20° and (at 410 metres) 6·1°; in that of Garda 19° and (at 240 metres) 7·7°.[3] Even in the much smaller and shallower lakes in Central Italy a similar distribution of temperature has been found. Thus in the Lago di Bolsena, the surface of which stands 305 metres above sea-level, the September temperature of the upper layer of water was found to range from 24·5° at the surface down to 24·1° at a depth of 10 metres. Below that point the thermometer steadily falls until at 30 metres it is only 9°, slowly sinking till in the bottom layers (at 140 metres) it reaches 7·2°. The temperature below a depth of 30 or 40 metres remains nearly uniform all the year.[4]

Geological functions.—Among the geological functions discharged by lakes the following may be noticed:—

1st. Lakes equalise the temperature of the localities in which they lie, preventing it from falling as much in winter and rising as much in summer as it would otherwise do. When a strong wind blows along a lake it drives forward the warm surface water. In consequence of this superficial current the colder water lower down is brought up to the surface, where it gets warmed by the sun and air as it is pushed towards the other end of the lake. By this transference a certain amount of circulation is brought about even in the water of a deep lake. The air above the chilly water that comes up to the surface is cooled, and on the other hand the bottom water is kept from remaining quite so cold. As an example of the equalising effect of a large lake on the climate of its surroundings, the Lake of Geneva is cited, the mean annual temperature of the water at its outflow being nearly 4° Fahr. warmer than that of the air.[5]

[1] For observations on the freezing of this and other lakes, see J. Y. Buchanan, *Nature*, xix. p. 412. On the deep-water temperature of lakes, A. Buchan, *Brit. Assoc.* 1872, Sects. p. 207.

[2] '*Proc. Roy. Soc. Edin.* xviii. (1890-91), p. 139.

[3] G. de Agostini, 'Il Lago d'Orta,' Turin, 1897, pp. 29, 32.

[4] G. de Agostini, "Esplorazioni idrografiche nei Laghi Vulcanici della Provincia di Roma," *Bol. Soc. Geog. Ital.* 1898, fasc. ii.

[5] The lakes of Sweden, which cover one-twelfth of the surface of the country, exercise an important influence on climate according as they are frozen or open. See Professor Hildebrandsson on the freezing and breaking up of the ice on the Swedish lakes, *Ann. Bur. Central Météorol. France*, 1878.

2nd. Lakes regulate the drainage of the area below their outfall, thereby preventing or lessening the destructive effects of floods.[1]

3rd. Lakes filter river-water and permit the undisturbed accumulation of new deposits, which in some modern cases may cover thousands of square miles of surface, and may attain a thickness of nearly 3000 feet (Lake Superior has an area of 32,000 square miles; Lago Maggiore is 2800 feet deep). How thoroughly lakes can filter river-water is typically displayed by the contrast between the muddy river which

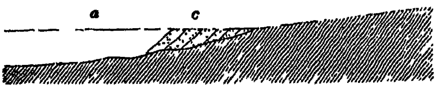


Fig. 141.—Section of a Delta-cone pushed by a brook into a lake.

flows in at the head of the Lake of Geneva, and the "blue rushing of the arrowy Rhône," which escapes at the foot.[2] The mouths of small brooks entering lakes afford excellent materials for studying the behaviour of silt-bearing streams when they reach still water.[3] Each rivulet may be observed pushing forward its delta composed of successive sloping layers of sediment (*ante*, p. 509). On a shelving bank, the coarser detritus may repose directly upon the solid rock of the district (Fig. 141). But as it advances into the lake, it may come to rest upon some older

Fig. 142.—Stream-detritus pushed forward over a previous lacustrine silt (*B.*).

lacustrine deposit (Fig. 142). The river Linth since 1860 has annually discharged into Lake Wallenstadt some 62,000 cubic metres of detritus.

A river which flows through a succession of lakes cannot carry much sediment to the sea, unless it has a long course to run after it has passed the lowest lake, and receives one or more muddy tributaries (see p. 509). Let us suppose, for example, that, in a hilly region, a stream passes

[1] As already stated (p. 446), winds blowing strongly down the length of a lake may raise the water-level and increase the volume of the outflow. If this takes place coincidently with a heavy rainfall, the flood of the escaping river is greatly augmented. These features are noticed in Loch Tay (D. Stevenson, 'Reclamation of Land,' p. 14). Hence, though, on the whole, lakes tend to moderate floods in the outflowing rivers, they may, by a combination of circumstances, sometimes increase them.

[2] When the Rhône reaches the Lake of Geneva its water rapidly sinks to the bottom, carrying with it the tribute of glacier mud with which it is charged. The cause of this sudden disappearance has been variously explained. M. Delebecque quotes the experiments of M. Schloesing, which showed that when the proportion of lime and magnesia in water falls below 0·06 gramme per litre, the clay in suspension is precipitated with extreme slowness. The proportion of the alkaline earths in the Lake of Geneva was found by M. Delebecque to be 0·0747 gramme per litre. 'Les Lacs Français,' p. 70.

[3] On the characters of lake-sediments, see a paper by Mr. Hutchings, *Geol. Mag.* 1894 p. 300.

through a series of lakes (*a*, *b*, *c*, in Fig. 143). As the highest lake will intercept much, perhaps all, of this sediment, the next in succession will receive little or none until the first is either filled up or has been drained by the cutting of a gorge through the intervening rock at *f*.

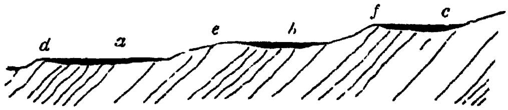


Fig. 143.—Filling up of a succession of Lakes (*B.*).

The same process will be repeated at *e* and *d* until the lakes are effaced, and their places are taken by alluvial meadows. Examples of this sequence of events are of frequent occurrence in Britain.[1]

Besides the detrital accumulations due to the influx of streams, there are some which may properly be regarded as the work of lakes themselves. Even on small sheets of water, the eroding influence of wind-waves may be observed; but on large lakes the wind throws the water

Fig. 144.—Beach-shingle, Lake Ontario, from a photograph by G. K. Gilbert, U. S. Geol. Survey.

into waves which almost rival those of the ocean in size and destructive power. Barriers, bars, beaches, sand-dunes, shore-cliffs and other familiar features of the meeting-line between land and sea, re-appear along the margins of such fresh-water seas as the Great Lakes of North America (Fig. 144). Beneath the level of the water a terrace or platform is formed, of which the distance from shore and depth vary with

[1] Much information regarding the details of the distribution of sediment over the bottom of lakes will be found in the work of M. Delebecque quoted above.

the energy of the waves by which it is produced. This platform is well developed in the Lake of Geneva.[1] In climates where the winters are severe enough to freeze the lakes, important geological changes are wrought on the shores by ice (*postea*, p. 532).

Some of the distinctive features of the erosion and deposition that take place in lake-basins have been admirably laid open for study in those basins of vanished lakes which have been so well described by Gilbert, Dutton, Russell and Upham in the Western Territories of the United States. They have been treated of in a masterly way by Gilbert in his essay on "The Topographic Features of Lake-shores."[2]

4th. Lakes serve as basins in which chemical deposits may take place. Of these the most interesting and extensive are those of iron-ore, which chiefly occur in northern latitudes (pp. 186, 612).[3] Extensive accumulations of calcareous tufa were formed along the margins of the great Pleistocene lakes of the Great Basin of North America. The highest terrace of Lake Bonneville contains tufa in which fresh-water shells are enclosed.[4]

5th. Lakes furnish an abode for a lacustrine fauna and flora, receive the remains of the plants and animals washed down from the surrounding country, and entomb these organisms in the growing deposits, so as to preserve a record of the lacustrine and terrestrial life of the period during which they continue. Besides the more familiar pond-snails and fishes, the largest lakes possess a peculiar pelagic fauna, consisting in large measure of entomostracous crustaceans, distinguished more especially by their transparency.[5] These, as well as the organisms of shallower water, doubtless furnish calcareous materials for the mud or marl of the lake-

[1] D. Colladon, *Bull. Soc. Géol. France* (3), iii. p. 661.

[2] G. K. Gilbert, *2nd Ann. Rep. U. S. G. S.* (1880-81); *5th Ann. Rep. U. S. G. S.* 1885; "Lake Bonneville," *Mon.* i. *U. S. G. S.* 1890; Dutton, *2nd Report* of same Survey, 1880-81, p. 169; I. C. Russell, *3rd Rep. U. S. G. S.* 1881-82, p. 195; *4th Report*, 1882-83, p. 435; *8th Report*, 1886-87, p. 201; and his "Geological History of Lake Lahontan," which forms *Monograph* xi. (1885) of same Survey; W. Upham on the beaches and terraces of a former glacial lake (Lake Agassiz), *Bull. U. S. G. S.* No. 39 (1887); *8th Ann. Rep. Geol. and Nat. Hist. Surv. Minnesota* (1879), pp. 84-87; "The Glacial Lake Agassiz," *Monog.* xxv. *U. S. G. S.* 1895; H. W. Turner on a vanished lake in Mohawk Valley, Plumas County, California, *Bull. Phil. Soc. Washington*, xi. (1891), p. 385.

[3] For an elaborate paper on these lake-ores (See-erze), see Stapff, *Z. Deutsch. Geol. Ges.* xviii. pp. 86-173; also A. F. Thoreld, *Geol. Fören. Stockholm Förh.* iii. p. 20; and *postea*, Sect. iii. p. 612.

[4] "Lake Bonneville," pp. 167, 209.

[5] F. A. Forel, *Archives d. Sciences*, Sept. 1882; "La Faune profonde des Lacs Suisses," *Mém. Soc. Helvét. Sci. Nat.* xxix., Zurich, 1885. O. E. Imhof, *Ann. Mag. Nat. Hist.* 1884, p. 69. Dr. E. Penard, "Les Rhizopodes de la Faune profonde dans le Lac Leman," *Revue Suisse de Zoologie*, vii. (1899). C. A. Davis, "A Contribution to the Natural History of Marl," *Journ. Geol.* viii. (1900), p. 485, and ix. (1901), p. 491. This writer has found that the algæ *Chara* and *Schizothrix* are the chief agents in forming the marl in the Michigan lakes, and that the deeper parts of these lakes are generally free from any thick deposits of a calcareous nature. The *Chara* has not been recorded as living at a greater depth than seven to nine metres, and it is in the water above that limit that the main accumulation of marl appears to take place.

bottoms. Many fresh-water plants also precipitate carbonate of lime on their surfaces or secrete it within their cells. The stonewort (*Chara*) is particularly effective as an agent in abstracting the lime from solutions in lake-water and in forming lacustrine marl.

But it is as receptacles of sediment from the land, and as localities for the preservation of a portion of the terrestrial fauna and flora, that lakes present their chief interest to a geologist. Their deposits consist of alternations of sand, silt, mud, gravel and occasional irregular seams of vegetable matter, together with sheets of calcareous marl (p. 612). In lakes receiving much sediment, little or no marl can accumulate during the time when sediment is being deposited. In small, clear and not very deep lakes, on the other hand, where there is little sediment, or where it only comes occasionally at intervals of flood, beds of white marl, sometimes 20 or 30 feet deep, formed entirely of organic remains, may gather on the bottom, as has happened in numerous districts of Scotland, Ireland, and in Michigan and the adjoining States. The fresh-water limestones and clays of some old lake-basins (those of Miocene time in Auvergne and Switzerland, and of Eocene age in Wyoming, for example) cover areas occasionally hundreds of square miles in extent, and attain a thickness of hundreds, sometimes even thousands, of feet.

Existing lakes are of geologically recent origin. Their disappearance is continually in progress by infilling and erosion. Besides the displacement of their water by alluvial accumulations, they are lowered and eventually drained by the cutting down of the barrier at their outlets. Where they are effaced merely by erosion, it must be an excessively slow process, owing to the filtered character of the water (p. 522); but where it is performed by the retrocession of a waterfall at the head of an advancing gorge, it may be relatively rapid after it has once begun.[1] In a river-course it is usual to find a lake-like expansion of alluvial land above each gorge. These plains may be regarded as old lake-bottoms, which have been drained by the cutting out of the ravines (p. 502). Successive terraces often fringe a lake and mark former levels of its waters.[2] It is when we reflect upon the continued operation of the agencies which tend to efface them, that we can best realise why the lakes now extant must necessarily be of comparatively modern date. Their modes of origin are further discussed in Book VII.

2. **Saline Lakes**, considered chemically, may be grouped as *salt lakes*, where the chief constituents are sodium and magnesium chlorides with magnesium and calcium sulphates; and *bitter lakes*, which are usually distinguished by their large percentage of sodium carbonate as well as chloride and sulphate (natron-lakes), sometimes by their proportion of borax (borax lakes). From a geological point of view they may be divided into two classes—(1) those which owe their saltness to the

[1] The level of the Lake of Geneva is said to have been lowered about six and a half feet since Roman times (Dausse, *Bull. Soc. Géol. France* (3), iii. p. 140); but this may perhaps be explicable in part at least by diminution in the water supply.

[2] For striking examples of such terraces, see those of the vanished Lake Bonneville, as described and figured in Mr. Gilbert's great monograph above cited.

evaporation and concentration of water poured into them by their feeders; and (2) those which were originally parts of the ocean.

(*a*) Salt and bitter lakes of terrestrial origin are abundantly scattered over inland areas of drainage in the heart of continents, as in Utah and adjacent territories of North America, and on the great plateau of Central Asia. These sheets of water were doubtless fresh at first, but they have progressively increased in salinity, because, though the water is evaporated, there is no escape for its dissolved salts, which consequently remain in the increasing concentrated liquid. In Ladâkh, extensive lakes formed by the ponding back of valley waters by alluvial fans, have grown saline and bitter, and have become the site of deposits of rock-salt and soda.[1]

The Great Salt Lake of Utah, which has been so carefully studied by Gilbert and other geologists, may be taken as a typical example of an inland basin, formed by unequal subterranean movement that has intercepted the drainage of a large area,

Fig. 145.—Terraces of Great Salt Lake, on the flanks of the Wahsatch Mountains.

wherein rainfall and evaporation, on the whole, balance each other, and where the water becomes increasingly salt from evaporation, but is liable to fluctuations in level, according to oscillations of meteorological conditions. The present lake occupies an area of rather more than 2000 square miles, its surface being at a height of 4250 feet above the sea. It is, however, merely the shrunk remnant of a sheet of water which covered an area of 19,750 square miles, and to which the name of Lake Bonneville has been given by Gilbert.[2] It is surrounded with slopes and mountains, along the sides of which well-defined lines of terrace mark former levels of the water (Fig. 145). The highest of these terraces lies about 1000 feet above the present surface of the lake, so that when at its greatest dimensions this vast sheet of water must have had a depth of about 1050 feet, its surface standing at a level of more than 5000 feet above the sea, and covering an area of 346 miles from north to south, and 145 miles in extreme width from east to west. It was then certainly fresh, for, having an outlet to the north, it drained into the Pacific Ocean, and in its stratified deposits a lacustrine molluscan fauna has been found.[3] According to Gilbert there are proofs that, previous to the great extension of

[1] F. Drew, 'Jummoo and Kashmir Territories.'

[2] The details of this remarkable piece of geological history will be found in Mr. Gilbert's monograph, already cited.

[3] For an account of this fauna, see R. E. Call, *Bull. U. S. Geol. Surv.* No. 11 (1884).

Lake Bonneville, there was a dry period, during which considerable accumulations of subaerial detritus were formed along the slopes of the mountains. A great meteorological change then took place, and the whole vast basin, not only that termed Lake Bonneville, but a second large basin, Lake Lahontan of King, lying to the west and hardly inferior in area, was gradually filled with fresh water. Again, another meteorological revolution supervened and the climate once more became dry. The waters shrank back, and in so doing left a remarkable succession of terraces as records of their successive levels. When they had sunk below the level of their outlet, they began to grow increasingly saline. The decrease of the water and the increase of salinity were in direct relation to each other, until the present degree of concentration has been reached, which is shown in the table (p. 529). The Great Salt Lake, at present having an extreme depth of less than 50 feet, is still subject to oscillations of level. These variations are partly annual, due to the melting of the snow on the neighbouring mountains, which makes the lake reach its maximum height in June, and partly non-periodic. When surveyed by the Stansbury Expedition in 1849, the water was 11 feet lower than in 1877, when the Survey of the 40th Parallel examined the ground. Since its discovery the lake has twice risen and twice fallen, the second fall being still in progress. Large tracts of flat land, formerly under water, are being laid bare. As the water recedes from them and they are exposed to the remarkably dry atmosphere of these regions, they soon become crusted with a white saliferous and alkaline deposit, which likewise permeates the dried mud underneath. So strongly saline are the waters of the lake, and so rapid the evaporation, as I found on trial, that one floats in spite of oneself, and the under surfaces of the wooden steps leading into the water at the bathing-places are hung with short stalactites of salt from the evaporation of the drip of the emergent bathers.[1]

Some of the smaller lakes in the great arid basin of North America are intensely bitter, and contain large quantities of carbonate and sulphate as well as chloride of sodium. The Big Soda Lake near Ragtown in Nevada contains 129·013 grammes of salts in the litre of water. These salts consist largely of chloride of sodium (55·42 per cent of the whole), sulphate of soda (14·86 per cent), carbonate of soda (12·96 per cent) and chloride of potassium (3·73 per cent). Soda is obtained from this lake for commercial purposes.[2]

(*b*) Salt lakes of oceanic origin are comparatively few in number. In their case, portions of the sea have been isolated by movements of the earth's crust; and these detached areas, exposed to evaporation, which is only partially compensated by inflowing rivers, have shrunk in level, and at the same time have sometimes grown much salter than the parent ocean.

The Caspian Sea, 180,000 square miles in extent, and with a maximum depth of from 2000 to 3000 feet, is a magnificent example. The shells living in its waters are chiefly the same as those of the Black Sea. Banks of them may be traced between the two seas, with salt lakes, marshes and other evidences to prove that the Caspian was once joined to the Black Sea, and had thus communication with the main ocean. In this case also there are proofs of considerable changes of water-level. At present the surface of the Caspian is 85½ feet below that of the Black Sea. The Sea of Aral, also sensibly salt

[1] Full information regarding the Great Basin and its lakes is to be found in vol. iii. of Wheeler's *Survey West of 100th Meridian*, vols. i. and iv. of the *Survey of the 40th Parallel*, and *Report of U. S. Geol. Survey*, 1880-81, and in the reports and monographs of Messrs. Gilbert and Russell cited on p. 524. See also J. E. Talmage, "The Waters of the Great Salt Lake," *Science*, xiv. (1889), p. 444.

[2] *Bull. U. S. G. S.* No. 9 (1884), p. 25. T. M. Chatard, *Amer. Journ. Sci.* xxxvi. (1888), p. 148, and xxxviii. (1889), p. 59. *B. U. S. G. S.* No. 60 (1890).

to the taste, was once probably united with the Caspian, but now rests at a level of 242·7 feet above that sheet of water. The steppes of south-eastern Russia are a vast depression with numerous salt lakes and abundant saline and alkaline deposits. It has been supposed that this depression continued far to the north, and that a great firth, running up between Europe and Asia, stretched completely across what are now the steppes and plains of the Tundras, till it merged into the Arctic Sea. Seals of a species (*Phoca caspica*) which may be only a variety of the common northern form (*Ph. fœtida*) abound in the Caspian, which is the scene of one of the chief seal-fisheries of the world.[1] On the west side of the Ural chain, even at present, by means of canals connecting the rivers Volga and Dwina, vessels can pass from the Caspian into the White Sea.[2]

The cause of the isolation of the Caspian and the other saline basins of that region is to be sought in underground movements which, according to Helmersen, are still in progress, but partly, and, in the case of the smaller basins, probably chiefly, in a general diminution of the water supply all over Central Asia and the neighbouring regions. The rivers that flow from the north towards Lake Balkash, and that once doubtless emptied into it, now lose themselves in the wastes and are evaporated before reaching that sheet of water, which is fed only from the mountains to the south. The channels of the Amur Darya, Syr Darya, and other streams bear witness also to the same general desiccation.[3] At present, the amount of water supplied by rivers to the Caspian Sea appears on the whole to balance that removed by evaporation, though there are slight yearly or seasonal fluctuations. In the Aral basin, however, there can be no doubt that the waters are progressively diminishing, the rate in the ten years between 1848 and 1858 having been 18 inches, or 1·8 inch per annum.

Owing to the enormous volume of fresh water poured into it by its rivers, the Caspian Sea is not, as a whole, so salt as the main ocean, and still less so than the Mediterranean Sea. Nevertheless the inevitable result of evaporation is there manifested. Along the shallow pools which border this sea, a constant deposition of salt is taking place, forming sometimes a pan or layer of rose-coloured crystals on the bottom, or gradually getting dry and covered with drift-sand. This concentration of the water is particularly marked in the great offshoot called the Karaboghaz, which is connected with the middle basin of the Caspian Sea by a channel 150 yards wide and 5 feet deep. Through this narrow mouth there flows from the main sea a constant current, which Von Baer estimated to carry daily into the Karaboghaz 350,000 tons of salt. An appreciable increase of the saltness of that gulf has been noticed; seals, which once frequented it, have forsaken its barren shores. Layers of salt are gathering on the mud at the bottom, where they have formed a salt-bed of unknown extent; and the sounding-line, when scarcely out of the water, is covered with saline crystals.[4]

The following table shows the proportions of saline ingredients in 1000 parts of the water of some salt lakes and inland seas :—

[1] Another variety or species of seal inhabits Lake Baikal. For an account of the structure and distribution of seals, see an interesting monograph by J. A. Allen in *Miscellaneous Publications of U. S. Geological and Geographical Survey of the Territories*, Washington, 1880.

[2] Count Von Helmersen, however, has stated his belief that for this extreme northern prolongation of the Aralo-Caspian Sea there is no evidence. The shells, on the presence of which over the Tundras the opinion was chiefly based, are, according to him, all fresh-water species, and there are no marine shells of living species to be met with in the plains at the foot of the Ural Mountains.

[3] *Bull. Acad. Imp. St. Pétersbourg*, xxv. (1879), p. 535. For an account of these rivers and Lake Aral, see H. Wood, *Journ. Roy. Geol. Soc.* xlv. (1875), p. 367, where an estimate is given of the annual amount of evaporation.

[4] Von Baer, *Bull. Acad. St. Pétersbourg* (1855-56). See also Carpenter, *Proc. Roy. Geog. Soc.* xviii. No. 4.

| Constituents (except where otherwise stated). | Caspian Sea. | | Indertsch Lake (Gobel). | Great Salt Lake, Utah (O. D. Allen). | Elton Lake, Kirghis Steppe (H. Rose). | Dead Sea, from a depth of 185 fathoms |
|---|---|---|---|---|---|---|
| | Near mouth of R. Ural (Gobel). | At Baku (Abich). | | | | |
| Chloride of Sodium . . | 3·673 | 8·5267 | 239·28 | 118·628 | 38·3 | 78·554 |
| ,, Magnesium | 0·632 | 0·3039 | 17·36 | 14·908 | 197·5 | 145·897 |
| ,, Calcium . | 0·013 ($MgCO_3$) | .. | . | .. | .. | 31 075 |
| ,, Potassium | 0·076 | trace | 1·01 | 0·862 (excess Chlorine) | 2·3 | 6·586 |
| Bromide of Magnesium | trace | . | 0·05 | .. | .. | 1·374 |
| Sulphate of Calcium . | 0·490 | 1·0742 | 0·42 | 0·858 | .. | 0·701 |
| ,, Potassium | 0·171 ($CaCO_3$) | 0·0554 ($CaCO_3$) | .. | 5·363 | .. | .. |
| ,, Magnesium | 1·239 | 3·2493 | 3·46 | 9·321 ($NaSO_4$) | 53·2 | .. |

**Deposits in Salt and Bitter Lakes.**—The study of the precipitations which take place on the floors of modern salt lakes is important in throwing light upon the history of a number of chemically formed rocks.[1] The salts in these waters accumulate until their point of saturation is reached, or until by chemical reactions they are thrown down. The least soluble are naturally the first to appear, the water becoming progressively more and more saline till it reaches a condition like that of the mother-liquor of a salt-work. Gypsum begins to be thrown down from sea-water, when 37 per cent of water has been evaporated, but 93 per cent of water must be driven off before chloride of sodium can begin to be deposited. Hence the concentration and evaporation of the water of a salt lake having a composition like that of the sea would give rise first to a layer or sole of gypsum, followed by one of rock-salt. This has been found to be the normal order among the various saliferous formations in the earth's crust. But gypsum may be precipitated without rock-salt, either because the water was diluted before the point of saturation for rock-salt was reached, or because the salt, if deposited, has been subsequently dissolved and removed. In every case where an alternation of layers of gypsum and rock-salt occurs, there must have been repeated renewals of the water supply, each gypsum zone marking the commencement of a new series of precipitates.

But from what has now been adduced it is obvious that the composition of many existing saline lakes is strikingly unlike that of the sea in the proportions of the different constituents. Some of them contain carbonate of sodium; in others the chloride of magnesium is enormously in excess of the less soluble chloride of sodium. These variations modify the effects of the evaporation of additional supplies of water now poured into the lakes. The presence of the sodium-carbonate causes the decomposition of lime salts, with the consequent precipitation of calcium-carbonate accompanied with a slight admixture of magnesium-carbonate,

[1] For the composition of the water of salt and bitter lakes, see the analyses collected by Roth in his 'Chemische Geologie,' i. p. 463 *et seq.*; also the great series of papers on the formation of salt-deposits by Messrs. Van't Hoff, Hinrichsen and Weigat in the *Sitzungsb. Berlin Akad.*, now in course of publication. The 24th paper (gypsum and anhydrite) appeared in the number of the *Sitzungsb.* for 21st November 1901. See also J. H. Van't Hoff and W. Meyerhoffer, *Zeitsch. physik. Chemie*, xxvii. (1899), p. 75.

while by further addition of the sodium-carbonate a hydrated magnesium-carbonate may be eventually precipitated. Hunt has shown that solutions of bicarbonate of lime decompose sulphate of magnesia with the consequent precipitation of gypsum, and eventually also of hydrated carbonate of magnesia, which, mingling with carbonate of lime, may give rise to dolomite.[1] By such processes the marls or clays deposited on the floors of inland seas and salt lakes may conceivably be impregnated and interstratified with gypseous and dolomitic matter; though in the Trias and other ancient formations which have been formed in enclosed saline waters, the magnesium-chloride has probably been the chief agent in the production of dolomite (*ante*, p. 426).

The Dead Sea, Elton Lake, and other very salt waters of the Aralo-Caspian depression, are interesting examples of salt lakes far advanced in the process of concentration.[2] The great excess of the magnesium-chloride shows, as Bischof pointed out, that the waters of these basins are a kind of mother-liquor, from which most of the sodium-chloride has already been deposited. The greater the proportion of the magnesium-chloride, the less sodium-chloride can be held in solution. Hence, as soon as the waters of the Jordan and other streams enter the Dead Sea, their proportion of sodium-chloride (which in the Jordan water amounts to from ·0525 to ·0603 per cent) is at once precipitated. With it gypsum in crystals goes down; also the carbonate of lime which, though present in the tributary streams, is not found in the waters of the Dead Sea. In spring, the rains bring large quantities of muddy water into this sea. Owing to dilution and diminished evaporation, a check must be given to the deposition of common salt, and a layer of mud is formed over the bottom. As the summer advances and the supply of water and mud decreases, while evaporation increases, the deposition of salt and gypsum begins anew.[3] As the level of the Dead Sea is liable to variations, parts of the bottom are from time to time exposed, and show a surface of bluish-grey clay or marl full of crystals of common salt and gypsum. Beds of similar saliferous and gypsiferous clays, with bands of gypsum, rise along the slopes for some height above the present surface of the water, and mark the deposits left when the Dead Sea covered a larger area than it now does. Save occasional impressions of drifted terrestrial plants, these strata contain no organic remains.[4]

Interesting details regarding saliferous deposits of recent origin, on the site of the Bitter Lakes, were obtained during the construction of the Suez Canal. Beds of salt, interleaved with laminæ of clay and gypsum-crystals, were found to form a deposit upwards of 30 feet thick extending 21 miles in length by about 8 miles in breadth. No fewer than 42 layers of salt, from 3 to 18 centimetres thick, could be counted in a depth of 2·46 metres. A deposit of earthy gypsum and clay was ascertained to have a thickness of 367 feet (112 metres), and another bed of nearly pure crumbling gypsum to be about 230 feet (70 metres) deep.[5]

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[1] Sterry Hunt, in 'Geology of Canada' (1863), p. 575. See also A. G. Högbom, "Ueber Dolomitbildung und dolomitischen Kalkorganismen," *Neues Jahrb.* i. (1894), p. 262.

[2] The Dead Sea, like the Great Salt Lake, was originally fresh, as proved by shells of *Melania*, &c., found in lacustrine terraces 1300 feet above its present level. Hull, 'Mount Seir,' 1885, pp. 100, 180.

[3] Bischof, 'Chem. Geol.' i. p. 397. Roth, 'Chem. Geol.' i. p. 476.

[4] Lartet, *Bull. Soc. Géol. France* (2), xxii. p. 450 *et seq.* Below the high terraces, containing lacustrine shells, evidence of shrinkage and concentration is supplied by gypseous marls and a bed of salt (30 to 50 feet), 600 feet above the present water-level.

[5] Lesseps, *Comptes rend.* lxxviii. p. 1740; *Ann. Chim. et Phys.* (5), iii. p. 189. Bader, *Verh. Geol. Reichsanst.* 1869, p. 288.

The desiccated floors of the great saline lakes of Utah and Nevada have revealed some interesting facts in the history of saliferous deposits. The ancient terraces marking former levels of these lakes are cemented by tufa, which appears to have been abundantly formed along the shores where the brooks, on mingling with the lake, immediately parted with their lime. Even at present, oolitic grains of carbonate of lime are to be found in course of formation along the margin of Great Salt Lake, though carbonate of lime has not been detected in the water of the lake, being at once precipitated in the saline solution. The site of the ancient salt lake which has been termed Lake Lahontan displays areas several square miles in extent covered with deposits of calcareous tufa, 20 to 60 and even 150 feet thick. This tufa, however, presents a remarkable peculiarity. It is sometimes almost wholly composed of what have been determined to be calcareous pseudomorphs after gaylussite (a mineral composed of carbonates of calcium and sodium with water) — the sodium of the mineral having been replaced by calcium. When this variety of tufa, distinguished by the name of *thinolite*, was originally formed, the waters of the vast lake must have been bitter, like those of the little soda-lakes which now lie on its site—a dense solution in which carbonate of soda predominated. On the margin of one of the present soda-lakes, crystals of gaylussite now form in the drier season of the year. Yet no trace of carbonate of lime has been detected in the water. The carbonate of lime in the crystals must be derived from water which on entering the saline lakes is at once deprived of its lime.[1]

## § 5. Terrestrial Ice.

Fresh water, under ordinary circumstances, when it reaches a temperature of 32° Fahr. passes into the solid state by crystallising into ice. In this condition it performs a series of important geological operations before being again melted and relegated to the general mass of liquid terrestrial waters. Five conditions under which ice occurs on the land deserve notice, viz., frost, frozen rivers and lakes, hail, snow and glaciers.

**Frost.**—Water, if perfectly still, may fall below the freezing-point without freezing, but when it is then moved, it at once freezes over. In freezing, water expands, so that 100 volumes become 109. If it be confined in such a way that expansion is impossible, it remains liquid even at temperatures below the freezing-point; but the instant that the pressure is removed this chilled water becomes ice. There is a constant effort on the part of the water to expand and become solid, very considerable pressure being needed to counterbalance this expansive power, which increases as the temperature sinks. At 30° Fahr. the pressure must amount to 146 atmospheres, or the weight of a column of ice a mile high, or 138 tons on the square foot. Consequently, when the water freezes at a lower temperature, its pressure on the walls of its enclosing cavity must exceed 138 tons on the square foot. Bombshells and cannon filled with water and hermetically sealed have been burst in strong frosts by the expansion of the freezing water within them. In nature, the enormous pressures which can be obtained artificially occur rarely or not at all, because the spaces into which water penetrates

[1] King, *Exploration of the 40th Parallel*, i. p. 510. I. C. Russell, *3rd Ann. Rep. U. S. G. S.* (1883), p. 211, and his monograph on "Lake Lahontan." T. M. Chatard on "Natural Soda," *Bull. U. S. G. S.* No. 60 (1890). On the crystallographic form and chemical composition of the thinolite, E. S. Dana, *Bull. U. S. Geol. Surv.* No. 12 (1884).

can hardly ever be so securely closed as to permit the water to be cooled down considerably below 32° Fahr. before freezing. But ice forming in cavities at even two or three degrees below the freezing-point exerts an enormous disruptive force.

Soils and rocks, being all porous, usually contain a good deal of moisture, ranging from a half of 1 per cent of their weight up to 20, or even, in the case of clay, 25 per cent. By the freezing of this interstitial water the particles of the rocks are separated from each other. Stones, stumps of trees, or other objects imbedded in the ground, are squeezed out of it. When a thaw comes, the soil seems as if it had been ground down in a mortar. Water, freezing in the innumerable joints and fissures of rocks, exerts great pressure upon walls between which it lies, pushing them asunder as if a wedge were driven between them. When this ice melts, the separated masses do not return to their original position. Their centre of gravity in successive winters becomes more and more displaced, until the sundered masses fall apart. In mountainous districts, where the winters are severe, and in high latitudes, much waste is thus produced on exposed cliffs and loose blocks of rock. Some measure of its magnitude may be seen in the heaps of angular rubbish which in these regions so frequently lie at the foot of crags and steep slopes. At Spitzbergen and on the coast of Greenland, the observed amount of destruction caused by frost is enormous. The short warm summer, melting the snow, fills the pores and joints of the rocks with water, which when it freezes splits off large blocks, launching them to the base of the declivities, where they are further broken up by the same cause. In some countries where the winters are severe, the soil-cap has been observed to be pushed or to creep downhill from the action of frost.[1]

**Frozen Rivers and Lakes.**—In countries such as Canada, the lakes and rivers are frozen over in winter with a cake of ice 1½ to 2½ feet thick. This cake, as it forms, expands and presses against the shores. A continuance of frost leads to a contraction of the ice already formed and to the consequent opening of vertical fissures, into which the water from below ascends and freezes. When a subsequent rise in temperature causes an expansion of the superficial crust, the ice once more presses against the shores. When these are steep, the ice yields and either breaks up along its margin or assumes an undulating surface over the lake; but where they are sloping, it is pushed up the slope, carrying with it earth and boulders. Similar results are repeated during subsequent rises and falls of temperature, the débris being driven farther up the shore, until it sometimes accumulates in a mound or wall along the outer edge of the broken ice. When the ice melts, this embankment of displaced material is left as a memorial of the severity of the climate. Such "shore-walls" are of common occurrence on the margins of many lakes in Canada and the United States.[2] Under certain conditions, also,

[1] Kerr, *Amer. Journ. Sci.* xxi. (1881), p. 345; O. Davison, *Geol. Mag.* 1889, p. 255.

[2] C. A. White, *Amer. Naturalist*, ii. (1868), p. 148. G. K. Gilbert, *5th Ann. Rep. U. S. Geol. Survey*, 1885, p. 109; "Lake Bonneville," p. 71.

"anchor-ice" (p. 189) forms on the bottoms of the rivers and rises to the surface.[1] In several ways, geological changes are thus effected. Mud, gravel, and boulders encased in the anchor-ice, or pushed along by it on the bottom, are moved from their position. This ice, formed in considerable quantity in the rapids of the Canadian rivers, is carried down stream and accumulates against the bars and banks, or is pushed over upon the surface of the upper ice. By its accumulation a temporary barrier is formed, the bursting of which causes destructive floods. When the ice breaks up in early summer, cakes of it which have been formed along-shore, and have enclosed beach-pebbles and boulders, float off so as either to drop these in deeper water or to strand them on some other part of the shore.

This kind of transport takes place on a great scale on the St. Lawrence. The islets of boulder-clay and solid rock are fringed with blocks which have been stranded by ice and which are ready to be again enclosed and floated off farther down stream. Should a gale arise during the breaking up of the frost, vast piles of ice, with mingled gravel and boulders, may be driven ashore and pushed up the beach; even blocks of stone of considerable size are sometimes forced to a height of several yards, tearing up the soil on their way, and helping to form a bank above the water-level. In the same river, great destruction of banks has been caused by rafts of ice, and particularly of anchor-ice. Crab Island, for example, which was about an acre and a half in extent at the beginning of this century, has entirely disappeared, its place being indicated merely by a strong ripple of the water, which is every year getting deeper over the site.[2] Other islands have also been destroyed. Great damage is frequently done to quays and bridges in the same region, by masses of river-ice driven against them on the arrival of spring. Reference has already been made to the increased power of transport and erosion acquired by frozen rivers, and especially when, as in Siberia, their ice breaks up in the higher parts of their courses, before it gives way in the lower (p. 493).

**Hail**, the formation of which is not yet well understood,[3] falls chiefly in summer and during thunderstorms. When the pellets of ice are frozen together so as to reach the ground in lumps as large as a pigeon's egg, or larger, great damage is often done to cattle, flying birds, and vegetation. Trees have their leaves and fruit torn off, and farm crops are beaten down.[4]

**Snow.**—In those parts of the earth's surface where, either from geographical position or from elevation into the upper cold regions of the atmosphere, the mean annual temperature is below the freezing-point, the condensed moisture falls chiefly as snow, and remains in great measure unmelted throughout the year. A line, termed the *snow-line*, can be traced, below which the snow disappears in summer, but above

[1] These conditions, according to Dr. Rae (*Nature*, xxi. p. 538), are: 1st, a rocky or stony bottom; 2nd, shallow water as compared with that higher up the stream; 3rd, a swifter current and rougher water, in comparison with a smooth and slower motion immediately above. It is a loose, slushy, adhesive kind of ice. See also *Nature*, xxi. p. 612; xxii. pp. 31, 54.

[2] Bleasdell, *Q. J. Geol. Soc.* xxvi. p. 669; xxviii. p. 292.

[3] For an account of the different theories proposed to account for hail, see Professor Viguier, *Assoc. Française*, 1879, p. 543; 1880, p. 486.

[4] For an illustration of this destructive action, see *Nature*, xlvii. (1893), p. 573.

which it continues to cover the whole or great part of the surface. The snow-line comes down to the sea around the poles. Between these limits it rises gradually in level till it reaches its highest elevation in tropical latitudes. South of lat. 78° N. it begins to retire from the sea-level, so that on the coast of Northern Scandinavia it is already nearly 3000 feet above the sea. None of the British mountains quite reach it. In the Alps it stands at 8500 feet, on the Andes at 18,000 feet, and on the northern slopes of the Himalayas at 19,000 feet.

Snow exhibits two different kinds of geological behaviour: (1) conservative, and (2) destructive. (1) Lying stationary and unmelted, it exercises a protective influence on the face of the land, shielding rocks, soils and vegetation from the effects of frost. On low grounds this is doubtless its chief function. Occasionally snow carries down a considerable amount of dust which may be suspended in the air, and thus augments the soil, as is done by "blood-rain" (*ante*, p. 444). In wide snow-covered tracts, remote from rocky surfaces, it is possible to detect and gather the meteoric dust which falls on the pure white surface. Indirectly also snow contributes to the accumulation of new deposits, where it is swept off by wind, together with the fine dust of bared rocks and soils with which it is frozen into drifts (p. 440).

(2) The destructive action manifests itself in several different ways. *a.* When snow falls in a partially melted state it is apt to accumulate on branches and leaves, until by its weight it breaks them off, or even bears down entire trees. Great destruction is thus caused in dense forests. *b.* Snow accumulating on gentle slopes and slowly sliding downwards, pushes soil or loose stones down-hill. Considerable transport of rotted rock and boulders may thus arise.[1] *c.* Snow on steep mountain slopes is frequently during spring and summer detached in sheets from 10 to more than 50 feet thick and several hundred yards broad and long, which rush down as *avalanches* (Lawinen), sweep away trees, soil or rocks, and heap them up in the valleys.[2] Besides the destruction caused by the avalanche itself, sometimes much damage arises from the sudden violent wind to which it gives rise.[3] *d.* Another indirect effect of snow is seen in the sudden rise of rivers when warm weather rapidly melts the mountain snows. Many summer freshets are thus caused in Switzerland. It is to the melting of the snows, rather than to rain, that rivers descending from snowy mountains owe their periodical floods. Hence such rivers attain their greatest volume in summer. *e.* A curious destructive action of snow has been observed on the sides of the Rocky Mountains, where the drifting of snow-crystals by the wind in some of the passes has damaged and even killed the pine-trees, wearing

[1] H. Y. Hind, *Canadian Naturalist*, viii. (1878), pp. 967, 976.

[2] An avalanche near Ormons Dessus, Canton Vaud (Dec. 1882), piled up a mass of ice and snow 200 feet thick (some of the ice-blocks being 18 feet long), and covered 3 square km. of ground. *Nature*, xxvii. p. 181. Streams may be thus blocked up, as the Inn was at Süs in 1827. For accounts of avalanches, see J. Coaz, 'Die Lawinen in den Schweizeralpen,' Berne, 1881; and the memoir on the Altels example cited p. 548.

[3] *Geol. Mag.* 1888, p. 155.

away the foliage, cutting off the bark, and even sawing into the wood for several inches.[1]

**Ice-caps and Glaciers.**[2]—The slow movement and compression of the snow, which, by gravitation, creeps downward into valleys descending from snow-fields, gives rise to large bodies of ice. The snow in the higher regions is loose and granular. As it moves downward it becomes firmer, passing into the condition of *névé* or *firn* (p. 189). Gradually, as the separate granules are pressed together and the air is squeezed out, the mass assumes the character of blue compact crystalline ice, often with a marked stratified structure, arising from the successive deposits of snow and from the thawing and refreezing of the layers. From a geological point of view, this ice may be regarded as the drainage of the snowfall above the snow-line, as a river is the drainage of the rainfall. A glacier, like a river, is always in motion, though so slowly that it seems to be solid and stationary. It descends as a brittle, thick-flowing substance, like pitch or resin.[3] The motion is unequal in the different parts, the centre and surface moving faster than the sides and bottom, as was first ascertained through accurate measurement by J. D. Forbes, who found that in the Mer de Glace of Chamouni the mean daily rate of motion in the summer and autumn was from 20 to 27 inches in the centre, and from 13 to 19½ near the side. Helland has observed that on the west coast of Greenland the glacier of Jacobshavn, which is 14,000 feet broad and more than 1000 feet thick in the middle, has a remarkably rapid motion, its rate for twenty-four hours ranging from 48·2 feet to 64·8 feet. The ice of the fjord of Torsukatak, nearly five miles wide, moves

[1] Clarence King, *Exploration of 40th Parallel*, i. p. 527.

[2] On glaciers and their geological work, see De Saussure, 'Voyages dans les Alps,' § 535; Agassiz, 'Études sur les Glaciers,' 1840; Rendu, "Théorie des Glaciers de la Savoie," *Mém. Acad. Savoie*, x., translated into English, 1875; J. D. Forbes, 'Travels in the Alps,' 1843; 'Norway and its Glaciers,' 1853; 'Occasional Papers on Glaciers,' 1859; Tyndall, 'Glaciers of the Alps,' 1857; Mousson, 'Gletscher der Jetztzeit,' 1854; A. Heim, 'Handbuch der Gletscherkunde,' Stuttgart, 1885; E. Richter, 'Gletscher der Ostalpen,' Stuttgart, 1888. 'Meddelelser om Grönland, udgivne af Commissionen for Ledelsen af de geologiske og geografiske undersögelser i Grönland,' Copenhagen—a voluminous report by a Danish commission appointed to investigate the country. The first volume appeared in 1879, and the long series that has since been issued gives a detailed account of the physical geography, &c. 'Groenland: Expedition der Gesellschaft für Erdkunde zu Berlin, 1891-93,' E. von Drygalski, 2 vols. royal 8vo, pp. 556 and 571, with 58 plates, 10 maps, &c., Berlin, 1897; Chamberlin, 'Glacial Studies in Greenland,' *Journ. Geol.* ii. pp. 649, 768; iii. pp. 61, 198, 469, 565, 668, 835; iv. pp. 582, 632; v. p. 229; R. D. Salisbury, *Journ. Geol.* iii. p. 875; iv. pp. 469-810; H. F. Reid, *Nat. Geog. Mag.* iv. (1892), pp. 19-84; *16th Ann. Rep. U. S. G. S.* (1896), pp. 421-459; Gregory and Garwood on Spitzbergen, *Q. J. G. S.* liv. (1898), p. 197; lv. (1899), p. 681; G. F. Wright, 'The Ice Age in North America,' 1889; I. C. Russell, 'The Glaciers of North America,' pp. x. 210, Boston, 1897; 'The Greenland Ice-fields and Life in the North Atlantic,' by G. F. Wright and W. Upham, New York, 1896; 'Ice-work, Past and Present,' by Professor Bonney, 1896; Mr. Douglas Freshfield and Prof. Garwood on the glaciers of the higher Himalayas, *Geograph. Journ.* April and July 1902.

[3] See Professor Sollas, "An Experiment to illustrate the Mode of Flow of a Viscous Fluid," *Q. J. G. S.* li. (1895), p. 361; E. C. Case, *Journ. Geol.* iii. p. 918; R. M. Deeley, *Geol. Mag.* 1895, pp. 152, 408.

with a mean rate of 24 feet in a day; that of Karajak, four and a half miles broad, moves 30 feet daily. The branch of the inland ice which descends into the sea in the Bay of Angpadlartok between lat. 72½° and 75° has been found to show the highest rate of movement ever observed in a glacier, viz., 100 feet in 24 hours or more than 4 feet in an hour.[1] G. F. Wright, from observations made by him in Alaska, inferred that the Muir glacier there entered a sea-inlet at an average rate of 40 feet per day (70 feet in the centre and 10 feet near the margin) in the month of August 1886;[2] a more recent measurement by Dr. Reid in the summer of 1890 gave a maximum rate of only seven feet in a day.[3]

The consequence of this differential motion is seen in the internal banded structure of the ice, in the downward curvature of the transverse fissures (crevasses), and in the arrangement of the lines of rubbish thrown down at the termination, which often present a horse-shoe shape, corresponding to that of the end of the ice by which they were discharged.[4]

The ice which descends from the snow-fields assumes different forms, according to the size of the gathering-ground, the supply of ice, and the shape and slope of the surface over which it has to move. But though distinguishing names have been assigned to these various forms, they pass insensibly into each other. For geological purposes they may be arranged under the following subdivisions: 1st, Ice-caps or Plateau-glaciers; 2nd, Valley-glaciers; 3rd, Corrie- or hanging-glaciers; 4th, Re-cemented glaciers.

1. Ice-caps or Plateau-glaciers include the deep mantle of snow and ice which, in the Polar regions, covers the land and creeps out to sea. In high Arctic, and still more in Antarctic latitudes, land-ice, formed from the drainage of a great snow-field, attains its greatest dimensions. The land in these regions is buried under an ice-cap which ranges up to a thickness (in the South Polar circle) of 10,000 feet (2 miles) or even more. Greenland lies under such a pall of snow that all its inequalities, save only the steep mountain-crests and peaks near

[1] H. Rink, *Zeitsch. Ges. Erdkund.*, Berlin, xxiii. No. 5.

[2] *Amer. Journ. Sci.* xxxiii. (1887), p. 10; H. P. Cushing, *American Geologist*, 1891, p. 207; Hayes, *National Geographic Magazine*, iv. (1892), p. 150; Russell, *Amer. Journ. Sci.* xliii. (1892), p. 169, and his 'Glaciers of North America'; *5th Ann. Rep. U. S. Geol. Surv.* (1885).

[3] On the recent remarkable diminution of this glacier, see S. P. Baldwin, *Amer. Geol.* xi. (1893), p. 366.

[4] The cause of glacier motion has been a much-vexed question in physics. See besides the works above cited, J. Thomson, *Proc. Roy. Soc.* 1856-57; Mosely, *op. cit.* 1869; Croll, 'Climate and Time,' 1875; Hopkins, *Phil. Mag.* 1845; *Phil. Trans.* 1862; Helmholtz, *Heidelberg Verhandl. Nat. Med.* 1865, p. 194; *Phil. Mag.* 1866, p. 22; Pfaff, *Akad. Bayer.* 1876. A valuable history of the controversy regarding glacier motion has been prepared by Sir H. H. Howorth, *Mem. Proc. Manchester Lit. Phil. Soc.* iv. (1891); H. F. Reid, "The Mechanics of Glaciers," *Journ. Geol.* iv. (1896), p. 912. The conclusion to which the most recent researches point coincides essentially with that enunciated upwards of 50 years ago by J. D. Forbes, that the motion of a glacier "is that of a slightly viscous mass, partly sliding upon its bed, partly shearing upon itself under the influence of gravity." Trotter, *Proc. Roy. Soc.* xxxviii. p. 107.

the coast, are concealed. The snow, creeping down the slopes, and mounting over the minor hills, passes beneath by pressure into compact ice. From the main valleys great glaciers, like vast tongues of ice, several thousand feet thick, and sometimes many miles in breadth, push out to sea, where they break off in huge fragments that float away as icebergs.[1] Moreover, the islands and peninsulas which front the edge of the Greenland plateau have their independent snow-fields, from which large glaciers descend to the sea. On the American mainland, also, extensive snow-fields and glaciers exist in Alaska, which have been largely explored by the geologists of the United States since that territory was ceded to their country by Russia. A voluminous literature has already been devoted to the description of the physical geography of the region.[2]

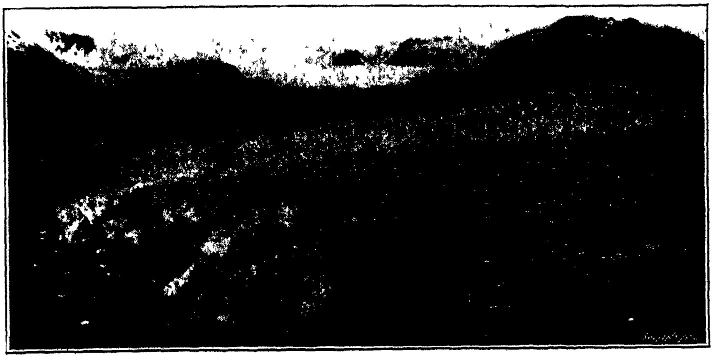


Fig. 146.—Front of Muir Glacier, Alaska, in June 1899. The ice-cliff is from 200 to 300 feet high. Photograph by Dr. G. K. Gilbert, U. S. Geol. Survey.

The vast snow-fields, ice-cap, and glaciers of the Antarctic regions are still very imperfectly known. As far back as 1777, Captain Cook gave interesting descriptions of the glaciers of South Georgia (lat. 54° S.), which reach the sea in a line of cliffs (Fig. 153). Further information was acquired last century by Weddel, Wilkes, D'Urville and more especially Sir James Ross. But it is hoped that large additions to our knowledge of the physical geography of the South Polar lands and seas

[1] The ice of Greenland has in recent years been closely studied by some of the observers whose works are cited on p. 535, especially the volumes of the Danish Commission and the writings of Messrs. Drygalski, Chamberlin, Salisbury, Reid, Wright and Upham. See also O. Mügge, *Neues Jahrb.* 1899, ii. p. 123; 1900, ii. p. 80; Drygalski, *op. cit.* 1900, i. p. 71; R. S. Tarr, *Amer. Geol.* xix. (1897), p. 262; *Bull. Geol. Soc. Amer.* viii. (1897), p. 251; C. Rabot, *Arch. Sci. Phys. Nat.*, Geneva, 1897, 1899-1900.

[2] The Alaskan glaciers and snow-fields have been described by various observers. See G. F. Wright's 'Ice Age in North America'; H. F. Reid, *Nat. Geog. Mag.* iv. (1892), p. 19; *16th Ann. Rep. U. S. G. S.* (1896), p. 421; I. C. Russell, *Journ. Geol.* i. p. 219; W. H. Dall, *17th Ann. Rep. U. S. G. S.* p. 850; J. E. Spurr, *20th Ann. Rep. U. S. G. S.* (1900), part vii. p. 252. 'The Ascent of Mount St. Elias, Alaska, by the Duke of the Abruzzi,' narrated by F. de Filippi, London, 1900 (with a bibliography in the Appendix).

will be gathered by the various expeditions which are now engaged in the exploration of that part of the globe.[1]

2. Valley-glaciers.—These, which were named by De Saussure "glaciers of the first order," are the largest bodies of ice which emerge from the snow-fields and extend sometimes for many miles down the valleys and well below the snow-line. They issue from isolated basins of snow which are separated from each other by the crests and peaks of the mountain ridges. Though naturally most abundantly developed in Arctic and Antarctic regions, they may be met with in any latitude wherever a

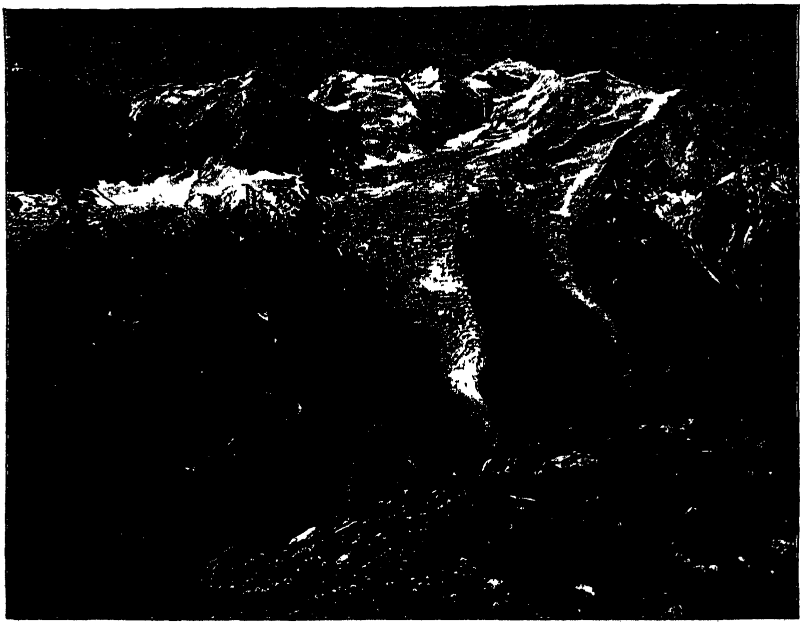


Fig. 147.—Snow-fields and Glaciers of Mont Blanc, seen from the top of Mont Brévent.

sufficiently extensive area of snow accumulates and remains permanent throughout the year. They are typically developed among the Alps, where they were first studied and whence most of our knowledge of the physics and geological action of glaciers, as well as many of the terms applied to glacial phenomena, have been derived. The separate basins of Alpine snow (Firnmulden) which nourish glaciers may average perhaps two square miles in area. The number of glaciers in the Alps has been estimated at 2000, covering a total area of from 3000 to 4000 square kilometres (Figs. 147, 148). They average perhaps from 3 to 5 miles in length. The Great Aletsch Glacier is nearly 10 (or, including the snow-field, nearly 15) miles long, with a mean breadth of 5900 feet, and descending to 4439 feet above the sea. The thickness of the ice in the

[1] See Arctowski, *Compt. rend.* cxxxi. (1900), p. 1260; *Bull. Soc. Belge Géol.* xv. (1901), p. 26; xvi. (1902), p. 61.

Alpine glaciers must often be as much as 800 to 1200 feet. It has been computed that the Gorner Glacier is large enough to make three cities as big as London.

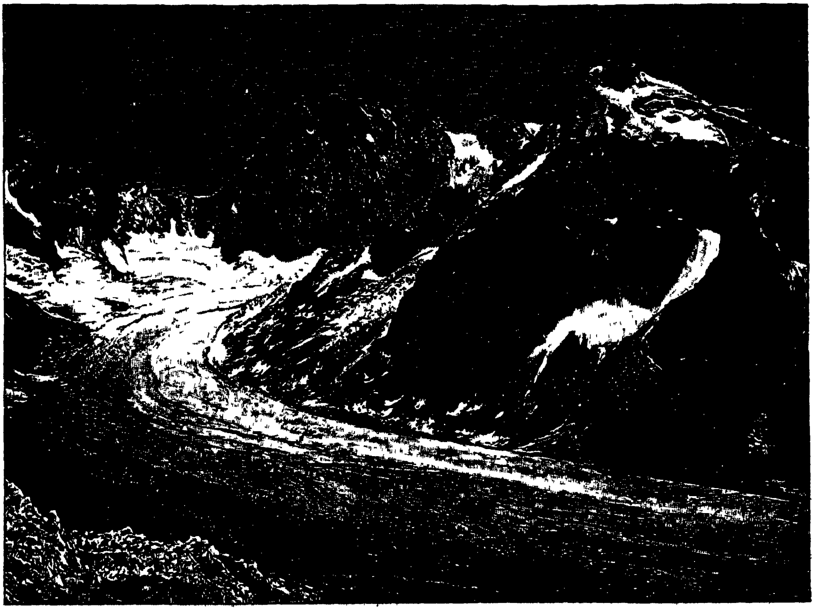


Fig. 148.—Glacier de Lechaud, with the Grandes Jorasses and Aiguille de Tacul.

On the great plateau of Scandinavia large snow-fields exist from which numerous glaciers descend (Figs. 149, 150, 151, 152). In Spitzbergen and in Greenland vast numbers of valley-glaciers radiate from independent

Fig. 149.—View of the two Glaciers of Fondalen, Holands Fjord, Arctic Norway.

basins of snow. Glaciers of large size are formed even in equatorial regions where the ground rises sufficiently high above the snow-line. They are found in great force among the Himalaya Mountains, while

among the Andes of Quito, close to the equator, many have been noted, the great mountain of Chimborazo (20,498 feet), for example, being capped with ice and sending glaciers out in all directions.[1] In the Rocky Mountains, once the seat of large glaciers, a few still linger. Those of Mount Rainier in Washington have been well described by Mr. Russell;[2] others are found in the Canadian portion of the mountain range.[3] In the southern hemisphere the mountain group of New Zealand rises high enough to keep perpetual snow and to nourish a number of typical glaciers.[4] From these examples of wide geographical distribution it is clear that the peculiar geological results effected by glacier-ice are not restricted to definite latitudes, but may be encountered, under the necessary limitations, from the equator to the poles.

(3) Corrie-glaciers (Hängegletscher) hardly creep beyond the high

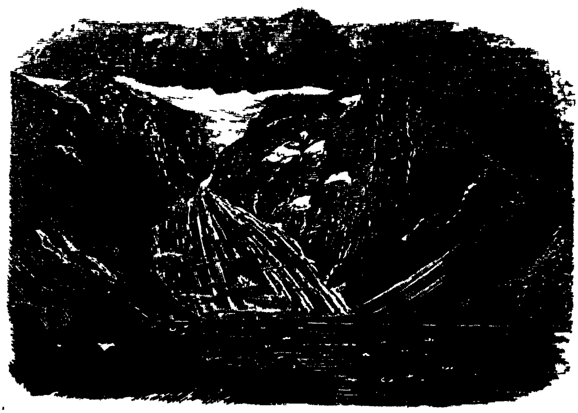


Fig. 150.—View of Re-cemented Glacier, Jökuls Fjord, Arctic Norway.

recesses wherein they are formed, and do not therefore reach as far as the nearest valley. Many beautiful examples of this type may be seen nestling in deep niches among the mountains along the steep declivities which intervene between the snow-covered plateau of Arctic Norway and the sea. They are common also in the Alps and in most glacier regions. They belong to what were originally termed "glaciers of the second order."

(4) Re-cemented Glaciers (*Glaciers remaniés*) consist of fragments which, falling from an ice-cliff crowning precipices of rock, are re-frozen at the bottom into a solid mass that creeps downward as a glacier. Probably the best illustrations in Europe are furnished by the Nus Fjord,

[1] On the glaciers of Ecuador, see Whymper, 'Travels among the Great Andes,' p. 348.

[2] *18th Ann. Rep. U. S. Geol. Surv.* (1898), pp. 355-423; *20th Ann. Rep.* part ii.; and 'Glaciers of North America,' already cited.

[3] A. Penck, *Zeitsch. Deutsch. u. Oester. Alpenv.* xxix. (1898), p. 55. *Appalachia*, ix. (1901), Nos. iii. and iv.

[4] A. P. Harper, *Geog. Journ.* i. (1893), p. 32; *op. cit.* v. (1895), p. 61; E. A. Fitzgerald, *op. cit.* vii. (1896), p. 483.

and other parts of the north of Norway. In some cases a cliff of "firn" resting on blue ice appears at the top of the precipice—the edge of the great "sneefond," or snow-field,—while several hundred feet below, in the corrie or cwm at the bottom, lies the re-cemented glacier, white at its upper edge, but acquiring somewhat of the characteristic blue gleam of compact ice as it moves towards its lower margin. A beautiful example of this kind was visited by me at the head of the Jökuls Fjord in Arctic Norway in 1865. When making the sketch from which Fig. 150 is taken, I observed that the ice from the edge of the snow-field above slipped off in occasional avalanches, which sent a roar as of thunder down the valley, while from the shattered ice, as it rushed down the precipices, clouds of white snow-dust rose into the air. The débris thus launched into the defile beneath accumulates there by mutual pressure into a tolerably solid mass, which moves downward as a glacier, and actually reaches the sea-level—the only example, so far as I am aware, of a glacier on the continent of Europe which attains so low an altitude.

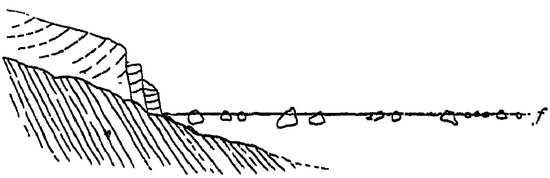



Fig. 151.—Section showing the production of Icebergs at the foot of the Jökuls Fjord Glacier.

As it descends it is crevassed; and when it comes to the edge of the fjord, slices from time to time slip off into the water, where they form fleets of miniature icebergs, with which the surface of the fjord (*f* in Fig. 151) is covered. Far more gigantic exhibitions of some of these operations are to be seen in North Greenland, where the great ice-cap of the interior advances to the edge of a cliff or steep declivity and breaks off in masses that accumulate at the base.

The body of a normal glacier is traversed throughout its length by a set of fissures called *crevasses*, which, though at first as close-fitting as cracks in a sheet of glass, widen by degrees as the glacier moves on, till they form wide yawning chasms, reaching, it may be, to the bottom of the ice, and travelling down with the glacier, but apt to be effaced by the pressing of their walls together again as the glacier winds down its valley. The glacier continues to descend until it reaches that point where its rate of advance is just equalled by its liquefaction. There it ends, its place down the rest of the valley being taken by the tumultuous river of muddy water which escapes from under the melting extremity of the ice. A prolonged augmentation of the snowfall will send the foot of the glacier farther down the valley; a diminution of the snowfall or a general rise of temperature will cause it to retreat farther up.

Considerable variations in the thickness and length of glaciers have been observed within the last two or three generations, and more minute investigation has traced

these oscillations back for some three hundred years.[1] It appears that the variations have an average period of thirty-five years, and that these coincide with variations in the climate, such as increased precipitation or increased evaporation and melting. Among the Alpine glaciers, which have been longer under observation than those of any other region, the glacier of La Brenva, on the Italian side of Mont Blanc, shrank to such an extent in the twenty-four years succeeding 1818, that its surface at one place was found to have subsided no less than 300 feet.[2] The glaciers of Mont Blanc had ceased to advance about 1854, and in twelve years, from 1854 to 1865, the Glacier des Bossons had receded 332 metres, that of Bois 188 metres, that of Argentière 181 metres, and that of Tour 520 metres. The retreat continued until 1875, when a number of glaciers began once more to advance, including all those of the Mont Blanc group, about half of those of the Valais, not more than a quarter of those in the Bernese Oberland, and only a few in the eastern Alps. In 1899 their partial increase had died out in the Swiss Alps, where only one glacier was then known to be advancing, nine were doubtful, and fifty-five were certainly or probably retreating. In the Eastern Alps, on the other hand, fifteen glaciers were advancing, thirteen were stationary, and more than twenty-two were retreating. Similar oscillations have been noted in the other glacier districts in both the old and new worlds. At present there appears to be a general diminution of the glaciers over the globe, though here and there an opposite movement is taking place.[3]

Some features of geological importance in the behaviour of a glacier as it descends its valley deserve mention here. When the ice has to travel over a very uneven floor, some portions may get embayed, while overlying parts slide over them. A massive ice-sheet may thus have many local eddies in its lower portions, the ice there even travelling for various distances, according to the nature of the ground, obliquely to the general flow of the main mass, as is remarkably displayed in the Greenland ice where it flows round the isolated rocks or "Nunatakker" which rise out of it. Travelling forward on successive "thrust-planes" (p. 690), it acquires a stratified or parallel structure, which in some places presents a close resemblance to the characteristic lenticular banded and plicated structure of many ancient gneisses.[4] This structure is well brought out by layers of dark detritus which are especially prominent along the sides and lower ends of the glaciers of North Greenland and Spitzbergen. At the foot of one of these glaciers the banding curves upward, so as to dip under the overlying ice and rise against the hill of detritus in front. Sometimes the layers become vertical and even bent double. The plasticity of the ice is further shown by the way in which the layers come up from the floor of the glacier to the surface, bringing with them the

[1] Brückner, 'Klima-Schwankungen seit 1700'; Penck, *Geog. Abhand.* 1890, iv.; Richter, "Geschichte der Schwankungen der Alpengletscher," *Zeitsch. Deutsch. u. Oester. Alp. Ver.* 1891; H. F. Reid, *Journ. Geol.* iii. p. 278.

[2] J. D. Forbes, 'Travels in the Alps,' p. 205.

[3] The variations in the glaciers of the world are now the subject of investigation and record by a Committee appointed by the International Geological Congress at Zurich in 1894. The annual reports of this Committee since that time will be found in the *Archives Sci. Phys. Nat.*, Geneva, and in the *Journal of Geology*, from which the facts above stated are taken, and to which the student is referred for further details.

[4] See by way of example the plates in the memoir on the glaciers and inland ice of Greenland by E. von Drygalski, *Zeitsch. Gesell. f. Erdkunde*, Berlin (1892); and the series of illustrations to the papers of Chamberlin and Salisbury in the *Journ. Geol.* cited *ante*, p. 535.

detritus that has been imbedded in them, and by the curvature which they frequently display round enclosed lenses of débris. This structure is further described on pp. 544-548.

In descending by a steep slope to a more level part of its course, a glacier becomes a mass of fissured ice in great confusion. It descends by a slowly creeping ice-fall, where a river would shoot over in a rushing waterfall. A little below the fall the fractured ice, with all its chaos of pinnacles, bastions and chasms, is pressed together again, and by regelation becomes once more a solid mass (Fig. 152).

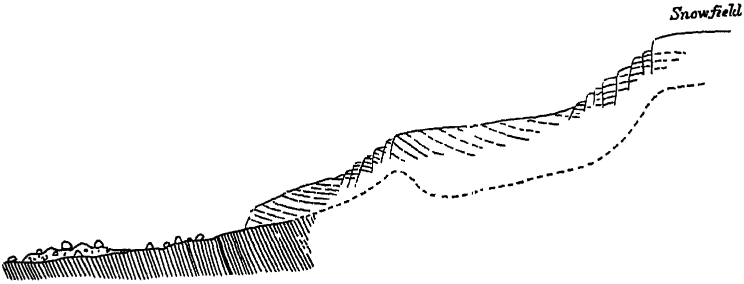



Fig. 152.—Section of Glacier with Ice-falls, Fondalen, Holands Fjord, Arctic Norway.

Great destruction is sometimes caused by the breaking off of the end of glaciers which terminate on steep ground. The sudden dislocation of the ice and its reduction to fragments, and even to powder, causes a considerable proportion of it to melt. A mingled mass of ice and water is thus discharged, which, meeting with loose moraine stuff, may speedily become a moving debacle of mud. Such, according to M. Forel, was the origin of the destructive avalanche which on 12th July 1892 swept away some thirty houses and killed about 150 people, in the valley of Montjoie, which joins that of the Arve, not far below Chamouni.[1]

Another incidental effect of the movement of glaciers is to be seen when the ice, barring the mouth of a tributary valley, dams back the streams flowing therein, and causes a lake to form. This result may be observed at the Märjelen See, on the great Aletsch Glacier, and elsewhere on the Alpine chain. If this arrest of the water is temporary, great damage may be done by the bursting of the ice-dam and the consequent sudden rush of the liberated water.[2] If, on the other hand, the glacier is massive enough to form a permanent barrier, the water may rise behind it so as to fill the tributary valley, and even escape by a pass at its head. Successive diminutions of the mass of ice will lead to corresponding lowerings of the level of the lake, each prolonged rest of the water at one level being marked by a shelf or terrace formed as a

[1] *Comptes rend.* cxv. (1892), p. 193. Other writers assign the bursting of a glacier-lake as the cause. Another memorable example of a similar catastrophe occurred above the Gemmi Pass three years later. 'Gletscherlawine an der Altels am 11 Sept. 1895,' by A. Heim and others ; Preller, *Geol. Mag.* 1896, p. 103.

[2] The instance of the bursting of the ice-dam in the Dranse valley has already been referred to (*ante*, p. 493).

beach-line along the shore. The famous "parallel roads" of Glen Roy are a striking illustration of this kind of geological history. (Book VI. Part V. Sect. i. § 1.)

Work done by Ice-sheets and Glaciers.—Sheets of land-ice, whether in the form of wide ice-caps or of more restricted glaciers, have three important geological tasks to perform—(1) to carry down the débris cast on their surface or enclosed in their mass; (2) to erode their beds; and (3) to distribute detritus over the lower grounds which they reach.

(1) *Transport.*—In ordinary glaciers such as those of Norway and the Alps, the transport of detritus takes place chiefly on the surface of the ice. Descending its valley, the glacier receives and bears along on its margin the dust, earth, stones and rubbish which, blown by wind, loosened by frost, or washed down by rain and rills, come from the cliffs and slopes. In this part of its work the glacier resembles a river which carries down branches and leaves from the woods on its banks. The detritus which rests on the surface of the ice sometimes so completely conceals it that the glacier looks like a plain of bare earth and stones. On this surface huge masses of rock—sometimes as big as a large cottage,—though seemingly at rest, are slowly travelling down the valley with the ice, liable at any moment to slip into the crevasses which may open below them. When they thus disappear, they may descend to the bottom of the ice, and move with it along the rocky floor, which is no doubt the fate of a large proportion of the smaller stones and sand. But the large stones seem, sometimes at least, to be cast up again by the ice to the surface of the glacier at a lower part of its course.

Recent detailed study of the ice-cap and glaciers of North Greenland has revealed features in the transport of detritus by land-ice which had never before been seen so clearly or on so great a scale, and which possess much interest in their bearing upon the history of the Pleistocene glacial deposits of the northern hemisphere. The vast plateau of inland ice in Greenland consists, so far as we know, of one unbroken snow-field, above which no hills or mountains rise, except near its seaward margin. From the absence of bare rock, no stones or earth fall on the surface of this snowy expanse. The ice therefore carries no moraines until it reaches the projecting nunataks near the coast, and even there they are not specially numerous or of particularly large dimensions. Hence one great source of the material carried down by the Alpine glaciers is absent in the far north. From the shore crags and from the nunataks dust is blown inland which, when abundant, dirties the surface of the snow-field, but it does not appear to travel more than a very few miles from its source of origin. In all the Greenland glaciers examined by Professor Chamberlin and his party during the expedition of 1894, while the upper part of the ice was on the whole free from debris, the lower portion was invariably charged with rock-rubbish of various kinds for 100 or 150 feet above the bottom. This material was disposed in layers wherein the clay, earth and stones were dispersed without any regard to size, coarse and fine detritus occurring indis-

criminately in the same band. Large boulders were sometimes found in abundance in the lowest bands. So thickly piled together were these materials in the bottom of the ice that a layer 12 or 15 feet thick seemed to be almost wholly composed of black débris. By the melting of the ice a pile of rubbish accumulated below and in front of the terminal face of the glacier.

But though at first the upper and main mass of the ice, so far as it could be seen, appeared to be destitute of detritus, it was found towards the lower ends of a number of glaciers, and also at the edge of the great ice field, to be loaded with earth and stones, which had come up from below. Good sections were observed where the actual upward

Fig. 158.—View of Glacier in Possession Bay, South Georgia.

curving of the layers could be traced from the floor to the surface of the ice. The successive lines of rubbish, marking the outcrops of highly inclined or vertical bands thus brought up, followed each other in concentric lines across the breadth of the glacier for many hundreds of feet in horizontal distance. At one point, within half a mile from the edge of the main ice-cap, as many as eight of these ridges of drift could be seen on the ice, separated by intervals of twenty or thirty rods, sometimes closely approaching each other. Moreover, similar lines or ridges of débris formed by the uprise of bands in the ice parallel to the sides of the valley were observed, closely simulating lateral moraines, yet entirely derived from the bottom. It is thus evident that though little detritus falls on the surface of the Greenland ice, a very large amount of it is carried down in the lower parts.[1] Similar observations have been made in Spitzbergen by Professors Garwood and Gregory, who found the lower parts of the glaciers there to be so laden with rock-rubbish that they sometimes could not draw any sharp line between the

[1] Chamberlin, *Journ. Geol.* as quoted on p. 535, and Salisbury, *Journ. Geol.* iv. p. 798.

glacier and the floor of detritus below it.[1] The introduction of so much mineral matter retards the flow of the ice, so that the rate of movement of the lower layers is still further lessened, and the upper parts move over them.

It thus appears that whether on the ice, in the ice, or under the ice, a vast quantity of detritus is continually travelling with a glacier down towards lower ground. The rubbish lying on the surface is called *moraine* stuff. Naturally it accumulates on either side of a valley-glacier, where it forms the so-called *lateral moraines*. When two glaciers unite, their two adjacent lateral moraines are brought together, and travel thereafter down the centre of the glacier as a *medial moraine*. In Fig. 154 the left lateral moraine (3) of Glacier B unites with the right lateral

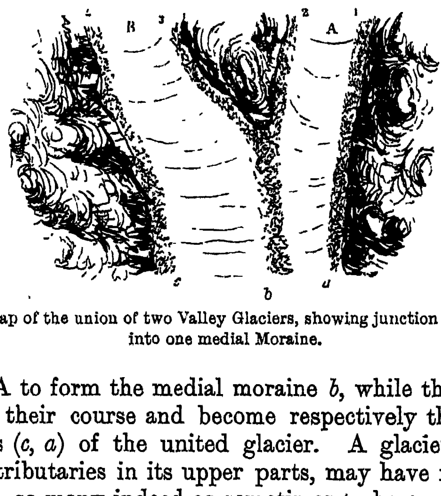



Fig. 154.—Map of the union of two Valley Glaciers, showing junction of two lateral into one medial Moraine.

moraine (2) of A to form the medial moraine *b*, while the other moraines (1, 4) continue their course and become respectively the right and left lateral moraines (*c*, *a*) of the united glacier. A glacier formed by the union of many tributaries in its upper parts, may have numerous medial lines of moraine, so many indeed as sometimes to be covered with débris, to the complete concealment of the ice. At such parts the glacier appears to be a bare field or earthy plain, rather than a solid mass of clear ice of which only the surface is dirty with rubbish. At the end of the glacier, the pile of loose materials is tumbled upon the valley in what is called the *terminal moraine*.

Beneath the ice of the Swiss glaciers lies a thin inconstant layer of fine wet mud, sand and stones, derived partly from the descent of materials from the surface down the crevasses, partly from the rocks of the sides and bottom of the glacier-bed. These materials may be seen fixed sometimes in the ice itself. Though it may locally accumulate, this layer is apt to be removed by the ice or by the water that flows under the glacier. It is known to Swiss geologists as the *moraine profonde* or *Grundmoräne* ( = boulder clay, till or bottom-moraine). The sheet of ice that once filled the broad central plain of Switzerland, between the Alps and the Jura, certainly pushed a vast deal of mud,

[1] *Q. J. G. S.* liv. (1898), p. 197.

sand and stones over the floor of the valley, and this material has been left as a covering, like the till of Northern Europe.[1]

It is among the Arctic ice-fields, however, that the moraine profonde is best developed. As above shown, the lower portions of the glaciers and even the marginal parts of the great ice-cap are abundantly charged with detritus. Owing to the remarkable way in which the bottom of the ice is pushed upward, the rock fragments with which it is laden are brought up to the surface, so as to form ridges there like ordinary superficial moraines. In Spitzbergen a marked difference was observed between the character of the detritus forming the two classes of moraines. In those of the common or Swiss type the materials carried along on the surface of the glaciers are rough, angular and ill assorted, with only rarely a block amongst them that showed the striation so characteristic of ice-erosion. In those, on the other hand, formed out of detritus carried along in and under the ice, the materials are subangular and rounded, with abundant scratched and polished pebbles and boulders stuck in a fine tough clay. This matrix is sometimes laminated, and the whole moraine may be well stratified, or in other cases entirely without any definite arrangement. There is obviously the closest resemblance between such deposits and the boulder-clay or till of Northern Europe and America.[2]

While the fact of the abundant distribution of detritus in the body of the Arctic ice-cap and glaciers is now well established, and of the most obvious interest and importance for the interpretation of Pleistocene glaciation, it presents some curious problems in the mechanics of glacier motion which require fuller consideration. That the detritus has not fallen from above but has been brought up from underneath admits of no doubt. Round the nunataks the ice stands back from the rock, leaving a trench or ravine into which the fragments from these projections will fall, so that little or none of the waste of these peaks can be carried on the surface of the ice; the whole or nearly the whole of it must find its way into the body or down to the bottom of the ice. Yet by some remarkable internal movement in the ice the detritus is arranged in parallel bands, as if it had been intermittently deposited in that form, and these bands are pushed upward until their outcrops reach the surface of the ice, across which they extend as long lines or ramparts of rubbish.

Professor Chamberlin recognised the formation of thrust-planes in some of the Greenland glaciers, and the riding forward of upper cleaner portions of the ice upon lower parts nearly laden with débris. More recently Professors Garwood and Gregory have observed similar facts in Spitzbergen. They explain the introduction of the detritus into the ice in the following manner. In a glacier which ends in a cliff-like face the lower portions, retarded by friction on the floor and by the amount of

[1] In 1869 I examined a characteristic section of an ancient *moraine profonde* near Solothurn, full of scratched stones, and lying on the striated pavement of rock to be immediately described as further characteristic of ice-action. It closely resembled the boulder-clay of Northern Europe.

[2] Garwood and Gregory, *op. cit.* p. 208.

detritus frozen into them, are outrun by the upper layers, which consequently project as a cornice. From time to time masses of this cornice fall off and accumulate in a pile below. If the glacier cannot push this pile forward it is forced to override it, and thus what was the upper part of the glacier becomes the base. "As the process is continuous, the glacier advances by an overrolling motion, the top layer falling to the bottom and then working upward over other fallen masses." These authors recognise three mechanical processes in the movement of the ice: (1) a simple flow like that of the Swiss glaciers, taking place mainly in the upper parts of the ice, which are free from detritus; (2) a continual series of deformations, the ice being crushed and fractured and thrust forward on shearing- or thrust-planes by the onward pressure of the mass of the glacier behind; (3) an overrolling movement where the upper layers, moving more rapidly than the lower, break off and accumulate as banks of ice-blocks, which in the end are re-cemented and driven onward as once more parts of the general body of the glacier.[1]

The explanation here summarised would account for the incorporation of bands of detritus at the lower end of an ice-cap or glacier, where alone the overrolling action is possible. It is not easy to see how it can be applied to the occurrence of the moraine-like ridges on the ice half a mile or more from the end, unless we could suppose that these inland ridges belong to an extremely remote time, when they were at the edge of the glacier, which has since then advanced by a succession of thrust-planes and overrollings to its present limit. More probably the phenomenon depends on some little understood peculiarities in the behaviour of Arctic ice and on the influence of an irregular topography upon its flow.[2]

(2) *Erosion.*—The manner and results of erosion in the channel of a glacier differ from those associated with other geological agents, and form therefore distinguishing features of ice-action. This erosion is effected partly by the pressure of the ice upon the rocks, partly by means of the fine sand, stones, and blocks of rock that fall between the ice and the rocks on which it moves. Ice pressed against masses of rock which have had their joints partly opened by frost may dislodge and remove them. Or the ice squeezed into clefts may disrupt the rocks along its side or its bed. An action of this kind, which has been called "plucking," seems to take place on the lee side of rocky prominences under a glacier.[3] Much more important, however, is the erosion effected by the sand and fragments of stone that the ice presses against the rocky surfaces over which it moves. This detritus is, for the most part, fresh and angular.

[1] *Q. J. G. S.* liv. (1898), pp. 203, 220.

[2] Mr. R. D. Salisbury (*op. supra cit.*) gives two sections explanatory of his conception of the structure of the Greenland glaciers. In the case of a small glacier he supposes that the layers of ice arrange themselves in a basin-shape with steep sides, up which the débris-bearing parts come to the surface, while in a large glacier he makes two basins with the rock-laden layers ridged up in an anticline along the centre.

[3] G. Steinmann, *Neues Jahrb.* i. (1899), p. 216; Baltzer, *Archiv. Sci. Phys. Nat.* 1892; *Zeitsch. prakt. Geol.* i. (1893), p. 14; *Denksch. Schweiz. Naturf. Ges.* xxxiii. (1893); G. E. Culver, *Journ. Geol.* iii. p. 982; O. Gumælius, *Geol. Fören. Stockholm*, xi. p. 249.

Its trituration by the glacier reduces the size of the particles, but retains their angular character, so that, as Daubrée has pointed out, the sand that escapes from the end of a glacier appears in sharp freshly-broken grains, and not as rounded water-worn particles.[1]

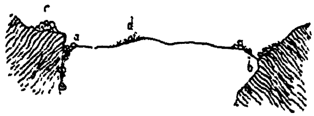


Fig. 155.—Section of a Glacier in its rocky channel,

With a medial moraine at *d*, a lateral moraine partly on the ice and partly stranded on a sloping declivity (*b*), a mass of rocks fallen between the ice and the precipitous rocks at *a*, and a group of perched blocks at *c* (J. D. Forbes).

The earth and stones strewn over the surface of a glacier are frequently precipitated into the crevasses, and may thus reach the rocky floor over which the ice is moving. They likewise fall into the narrow space which sometimes intervenes between the margin of a glacier and the side of the valley (*a* in Fig. 155). Held by the ice as it creeps along, they are pressed against the rocky sides and bottom of the valley so firmly and persistently as to descend into each little hollow and mount over each ridge, yet all the while moving along steadily in one dominant direction

Fig. 156.—View of part of the side of the Mer de Glace (J. D. Forbes).

with the general movement of the glacier. Here and there the ice, with grains of sand and pieces of stone imbedded in its surface, can be caught in the very act of polishing and scoring the rocks. In Fig. 156 a view

[1] 'Géologie expérim.' p. 254.

is given of the "angle" on the Mer de Glace, Chamouni, where blocks of granite are jammed between the mural edge of the ice and the precipice of rock along which it moves, and which is scored and polished in the direction of motion of the blocks. Tyndall long ago stated that a glacier 300 metres thick, allowing 12·20 metres of ice to an atmosphere, presses with a weight of 486,000 lbs. on every square yard of its bed,[1] and with a vertical pressure of this amount it moves down its valley. It is possible that the erosive power of the ice is assisted by the alternate freezing and thawing of the water that flows under the glacier. Minute joints and crevices may thus be widened and the particles of the rock may be separated, as those of soil and rock are at the surface by frost.[2]

Fig. 157.—Ice-worn surface of rock, showing Polish, Striæ, Groovings and Erratics. Sutherland.

Under the slow, continuous, and enormously erosive power of a glacier, the most compact resisting rocks are ground down, smoothed, polished and striated (Fig. 157). The striæ vary from such fine lines as may be made by the smallest grains of quartz up to deep ruts and grooves. They sometimes cross each other, one set partially effacing an older one, and thus pointing to shiftings in the movement of the ice. On the retirement of the glacier, hummocky bosses of rock, having smooth undulating forms like dolphins' backs, are conspicuous. These have received the name of *roches moutonnées*. The stones by which this scratching and polishing are effected suffer in exactly the same way. They are ground down and striated, and since they must move in the line of least resistance, or "end on," their striæ run in a general sense

[1] *Phil. Mag.* xxviii. (1864).

[2] A. Helland, *Geol. Fören. Stockholm*, ii (1874), pp. 286, 342.

lengthwise (Fig. 159). It will be seen, when we come to notice the traces of former glaciers, how important is the evidence given by these striated stones.

Besides its proper and characteristic rock-erosion, a glacier is aided in a singular way by the co-operation of running water. Among the Alps, during day in summer, much ice is melted, and the water courses over the glaciers in brooks which, as they reach the crevasses, tumble down in rushing waterfalls, and are lost in the depths of the ice. Directed, however, by the form of the ice-passage against the rocky floor of the valley, the water descends at a particular spot, carrying with it the sand, mud and stones which it may have swept away from the surface of the glacier. By means of these materials it erodes deep pot-holes (moulins) in the solid rock, in which the rounded detritus is left as the crevasse closes up or moves down the valley. On the ice-worn surface of Norway, singular cavities of this kind, known as "giants' kettles" or "caldrons" (Riesentöpfe, Riesenkessel, Fig. 158), exist in great numbers.[1] There can be little doubt that they have had an origin under the massive ice-cover which once spread over that peninsula. Similar cavities filled with transported boulders occur in the molasse sandstone near Berne,[2] and a large group of them is now one of the sights of Lucerne. They have

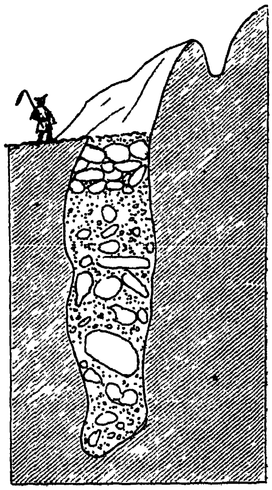


Fig. 158.—Section of "Giant's Kettle," near Christiania.

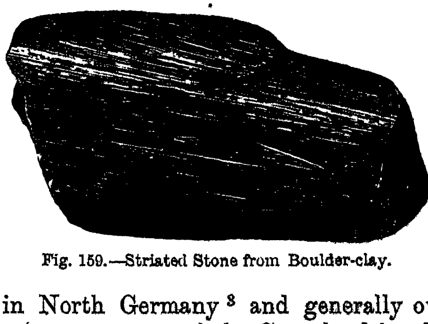


Fig. 159.—Striated Stone from Boulder-clay.

been recognised in North Germany[3] and generally over the glaciated areas of Europe. As some parts of the Greenland ice-sheet are traversed in summer by powerful rivers which are swallowed up in the crevasses, excavations of the same nature are no doubt also in progress there.

Since rocks present great diversities of structure and hardness, and

[1] S. A. Sexe, *Universit. Program. Christiania*, 1874; Brögger and Reusch, *Q. J. G. S.* xxx. p. 750; W. Upham, *Bull. Geol. Soc. Amer.* xii. (1900), p. 25.

[2] Bachmann, *Neues Jahrb.* 1875, p. 53.

[3] *Jahrb. Preuss. Geol. Landesanst.* 1880, p. 275.

consequently vary much in the resistance they offer to denudation, they are necessarily worn down unequally. The softer, more easily eroded portions are scooped out by the grinding action of the ice, and basin-shaped or various irregular cavities are dug out below the level of the general surface.[1] Similar effects may be produced by a local augmentation of the excavating power of a glacier, as where the ice is strangled in some narrow part of a valley, or where, from change in declivity, it is allowed to accumulate in greater mass as it moves more slowly onward. Such hollows, on the retirement of the ice, become receptacles for water, and form pools, tarns or lakes, unless, indeed, they chance to have been already filled up with glacial rubbish.

Among the proofs of great erosion by ice on hard rocky surfaces the existence of basins scooped out of the solid rock are perhaps the most striking. The striæ and scorings may in such cases be traced down below the water at the end of a tarn or lake, and may be found emerging at the other end with the same steady direction as on the surrounding ground or enclosing valley. In the year 1862 the late Sir A. C. Ramsay drew attention to this peculier power of land-ice, and affirmed that the abundance of excavated rock-basins in Northern Europe and America was due to the fact that these regions had been extensively eroded by sheets of land-ice, when the more northern parts of the two continents were in a condition like that of North Greenland at the present day. This explanation has given rise to prolonged controversy, many geologists upholding the doctrine of ice-erosion and others as strenuously denying it. Ramsay may have applied it too widely, but he has the great merit of having called attention to a *vera causa* in geology and of throwing a new light on the glaciated topography of the northern hemisphere. The origin of lakes will be further considered in Book VII.

While the proofs of great erosion by land-ice are indisputable, many instances have now been collected where glaciers have overridden moraines, gravel-beds or other soft material, and have moved across them for perhaps long periods without removing them. In Greenland, as above stated, it has been observed that the layers of débris-laden ice at the bottom of a glacier bend upward against the bank of rubbish thrown down in front, which in many cases does not seem to have been pushed forward or disturbed for some considerable time.[2] It is obvious that in such places the ice has at present no marked, or at least rapid, erosive power.

Undoubtedly the most obvious proof of the erosion effected by glaciers is to be found in the vast amount of mud which discolours the water that escapes from their lower ends. This sediment, unlike that of ordinary

[1] See the remarks already made (p. 458) on the possibility of the rotting out of basin-shaped receptacles in solid rock through the operations of superficial weathering—a process which may account for many rock-basins that have subsequently had their decomposed rock swept out of them by ice.

[2] For a striking example of the way in which a glacier may spread over deposits of gravel, see the plate accompanying Mr. H. P. Cushing's paper on the Muir Glacier of Alaska, *American Geologist*, 1891.

rivers, which become swollen and muddy according to the weather or the season, is always conspicuous, and proves that the ice is constantly creeping downward and in so doing is wearing down the rocks over which it passes. It is not so easy, however, as in the case of rivers to measure the amount of this glacial mud and to form an approximate idea of the amount and rate of the erosion. Various measurements and estimates have been made of this proportion of sediment and of the volume of water discharged by various glaciers.

From the end of the Aar glacier (which with its affluents is computed to have an area of 60 square kilometres, and is therefore by no means one of the largest in Switzerland) it has been estimated that there escape every day in the month of August two million cubic metres (440 million gallons) of water, containing 284,374 kilogrammes (280 tons) of sand. The amount of fine sand discharged from the melting glacier into the fjord of Isortok, Greenland, is estimated at 4062 million kilogrammes per day.[1] Mr. A. Helland has computed that from the Justedal glacier, Norway, one million kilogrammes of sediment are discharged in a July day, and that the total annual discharge from the ice-field, 830 square miles in area, amounts to 180 millions of kilogrammes, besides 13 million kilogrammes of mineral matter in solution. Taking the specific gravity of the suspended matter at 2·6, he finds that the basin of the glacier loses 69,000 cubic metres of solid rock every year, or a cubic mass measuring 41 metres on the side.[2] Among the Mont Blanc group of glaciers, Professor Duparc found that at the beginning of August 1890, the water from the Argentière glacier contained 535 grammes of sediment in every cubic metre of water, and at the same time in 1891, 139 grammes. The water from the Mer de Glace at the first date contained 483 and at the second 452 grammes. In that from the Bossons the quantities were 2287 and 325.[3] The mean quantity from seven Norwegian rivers was found to be 148 grammes in the cubic metre of water; from ten Greenland glaciers 634 grammes; from the Icelandic glaciers 975 grammes.[4] Mr. P. A. Oyen has estimated in micromillimetres the annual normal erosion of the basins of four northern glaciers as follows:[5]—

| | | |
|---|---|---|
| Iceland, | Vatnajökul | 647 |
| Norway, | Jostedalsbrae | 79 |
| ,, | Hardanger-jökul | 69 |
| ,, | Galdhötind | 54 |

(3) *Deposition of Detritus.*—It is obvious that as land-ice is a powerful agent in the transport of rock débris, it must play an important part in the distribution of detritus from high to low ground. While rivers are limited in their carrying power by their own velocity and the size of the materials with which they have to deal, glaciers have no similar limitation. Though they may move slowly, they are capable of conveying the most gigantic masses of rock for long distances, and leaving them in places hundreds or thousands of feet below their points of departure. Moreover, while rivers are always carrying their burden of detritus in a downward direction, glaciers sometimes climb slopes and push up their moraines and boulders to considerable heights.

When from any cause a glacier diminishes in size, it may drop its

[1] 'Meddelelser om Grönland,' vol. ii.

[2] *Geol. Fören. Stockholm*, 1874, No. 21, Band ii. No 7.

[3] *Archiv. Sci. Phys. Nat.*, Geneva, xxvi. (1891), p. 531.

[4] A. Helland, *op. supra cit.*; *Nyt. Archiv. Natur.* i.; *Archiv. Math. Natur.* 1882.

[5] *Nyt. Mag.* 1892; xxxvii. (1900), p. 112.

blocks upon the sides of its valley, and leave them there, sometimes in the most threatening positions. Such stranded stones are known as *perched blocks.* Those of each valley belong to the rocks of that valley; and if there be any difference between the rocks on the two sides, the perched blocks, carried far down from their sources, still point to that difference, for they remain on their own original side. But during a former great extension of the glaciers of the northern hemisphere, blocks of rock have been carried out of their native valleys, across plains, valleys, and even considerable ranges of hills.

Fig. 160.—Pierre à Bot—a granite block from the Mont Blanc range, stranded above Neufchâtel (J. D. Forbes).

Such "erratics" (Findlinge) not only abound in the Swiss valleys, but cross the great plain of Switzerland, and appear in numbers high upon the flanks of the Jura. Since the latter mountains consist chiefly of limestone, and the blocks are of various crystalline rocks belonging to the higher parts of the Alps, the proof of transport is irrefragable. Thousands of them form a great belt of boulders extending for miles at an average height of 800 feet above the Lake of Neufchâtel (Fig. 160). These consist of the protogine granite of the Mont Blanc group of mountains, and must have travelled

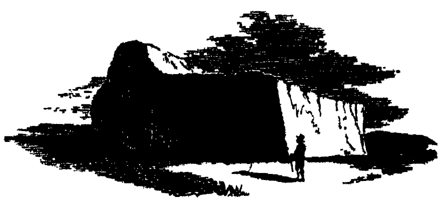


Fig. 161.—Angular erratic block on the north side of the Alpi di Pravolta, Lake of Como (*B.*).

at least 60 or 70 miles. One of the most noted of them, the Pierre à Bot (toad-stone), which lies about two miles west of Neufchâtel, measures 50 (French) feet in length by 20 in width and 40 in height. It is estimated to contain 40,000 cubic feet, and to weigh about 3000 tons.[1] The celebrated "blocks of Monthey" consist of huge masses of granite, disposed in a belt, which extends for miles along the mountain slopes of the left bank of the Rhône, near its union with the Lake of Geneva. On the southern side of the Alps, similar evidence of the transport of blocks from the central mountains is to be found. On the flanks of the limestone heights on the farther side of the Lake of Como, blocks of granite, gneiss and other crystalline rocks lie scattered about in hundreds.

[1] Forbes, 'Travels in the Alps,' p. 49.

Before the numerous facts had been collected and understood which prove a former great augmentation in the size of the Alpine glaciers, it was believed by many geologists that the erratics stranded along the flanks of the Jura Mountains had been transported on floating ice, and that Central Europe was then in great part submerged beneath an

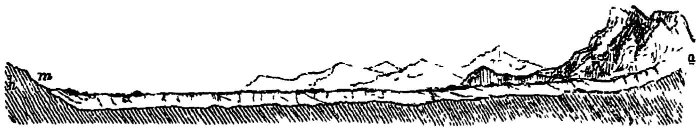



Fig. 162.—Section to show the extension of the Alpine Glaciers (*a*) across the Plain of Switzerland, and the transport of blocks to the sides of the Jura (*m*) (*B.*).

icy sea. It is now universally admitted, however, that the transport has been entirely the work of glaciers. Instead of being confined, as at present, to the higher parts of their valleys, the glaciers extended down into the plains. As already stated, they filled the great depression between the Oberland and the Jura, and, rising high upon the flanks of the latter chain, actually overrode some of its ridges (Fig. 162). Similar evidence in the hilly parts of Britain, as well as in other parts of Europe and America, no longer the abode of glaciers, shows that a great extension of snow and ice at a recent geological period prevailed in the northern hemisphere, as will be described in the account of the Glacial period in Book VI.

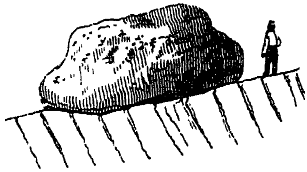


Fig. 163.—Block of Granite resting on inclined strata (*B.*).

As De la Beche has well pointed out, the student must be on his guard lest he be led to mistake for true erratics mere weathered blocks belonging to a rock that has disintegrated *in situ*. If, for example, he should encounter a block like that represented in Fig. 163, he would properly conclude that it had travelled, because it did not belong to the rock on which it lay. But he would require to prove further that there was no rock in the immediate neighbourhood from which it could have fallen as the result of mere weathering. The granite (*c*) shown in Fig. 164 disintegrates at the summit, and the blocks into which it splits find their way by gravitation down the slope.[1]

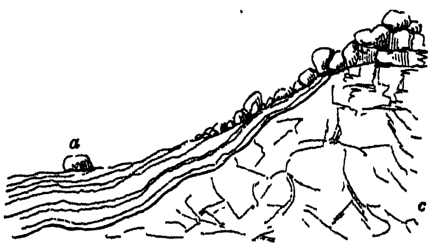



Fig. 164.—Granite (*c*) decomposing into blocks (*a*), which gradually roll down upon the surrounding stratified rocks (*B.*).

The moraines shed from the sides and ends of glaciers in the valleys remain as enduring memorials of the former presence of the ice. These

[1] De la Beche, 'Geological Observer,' p. 257. The surface of some parts of the granite districts of Cornwall is strewn with large boulders of granite, schorl-rock, vein-quartz, &c. ; but these, though resembling erratics in form, are all due to decomposition of the parent-rocks *in situ*.

heaps of débris may be seen running along the sides of a valley, where they mark the margin of the ancient glacier, and also arranged in crescent-shape across the valley, as they were thrown down from the melting front of the ice. Not infrequently a succession of such ridges may be traced up a valley, marking successive pauses with intervals of more rapid shrinkage of the ice. Occasionally lakes of water are still ponded back by these moraines; more frequently the barrier of detritus has been cut through by the escaping stream, and an alluvial plain or peat-bog may mark where the lake once lay.

Much more extensive must be the sheet of detritus left by the melting and disappearance of a plateau-glacier or ice-cap. Observations of the low ground from which the arctic ice has retreated show it to be strewn with earth and stones remarkably like the boulder-clay and "glacial-drift" which cover so much of Northern Europe and America. (Book VI. Part V. Sect. i. § 2.) Professors Garwood and Gregory found on the broad plain of the Booming Glacier, Spitzbergen, some square miles of a tough mud, with scratched boulders and pebbles, which only needed to be dried to form a perfect boulder-clay. This deposit had not been laid down as a moraine at the end of the glacier, but represented the detritus once enclosed in the ice and dropped when the ice melted and retreated to its present limits.[1]

## § 6. Oceanic Waters.

The area, depth, temperature, density and composition of the sea having been already treated of (Book II.), we have now to consider its place among the dynamical agents in geology. In this relation it may be studied under two aspects: 1st, its movements, and 2nd, its geological work.

I. **Movements.**—(1) *Tides.*[2]—These oscillations of the mass of the oceanic waters, caused by the attraction of the sun and moon, require notice here only as regards their geological bearings. They are scarcely perceptible in enclosed seas, such as the Mediterranean and Black Seas, which are commonly spoken of as tideless. In strictness, however, a feeble but quite recognisable tide may be observed in the Mediterranean. On the coast of the Alpes Maritimes it has a mean rise of 6 to 8 inches, the least rise being 4 and the highest not exceeding 10 inches. The Mediterranean tides are most strongly developed in the Bay of Gibraltar (where they rise from 5 feet to 6 feet 6 inches), the upper Adriatic, and the Gulf of Gabes. At Brindisi the rise is 8 inches, at Ancona 1 foot 4 inches, at Venice 1 foot 8 inches, and at Trieste 2 feet 4 inches. With a rise of the barometer the level of the water falls sometimes a fourth lower than the limit of the normal ebb. Observations at Nice, Monaco, Cannes, and other places show that from atmospheric disturbances the level of the sea may be lowered as much as 1 foot 8 inches.[3]

[1] *Q. J. G. S.* liv. (1898), p. 209.

[2] See 'The Tides and Kindred Phenomena in the Solar System,' by Professor G. H. Darwin, 1898, pp. xviii. 342.

[3] Haschert, *Deutsche Rundschau für Geographie*, July 1887. *Bull. Amer. Geograph. Soc.* xix. (1887), p. 314. J. de Pulligny, *Assoc. Franç.* 1891, ii. p. 287.

In a wide, deep ocean, the tidal undulation probably produces no perceptible geological change. It passes at a great speed; in the Atlantic, its rate is 500 geographical miles an hour. But as this is merely the passing of an oscillation whereby the particles of water are gently raised up and let down again, there can hardly be any appreciable effect upon the deep ocean-bottom. When, however, the tidal wave enters a narrow and shallow sea, it has to accommodate itself to a smaller channel, and encounters more and more the friction of the bottom. Hence, while its rate of motion is diminished, its height and force are increased. It is in shallow water, and along the shores of the land, that the tides acquire their main geological importance. They there show themselves in an alternate advance upon and retreat from the coast. Their upper limit has received the name of *high-water mark*, their lower that of *low-water*


Fig. 165.—Section of a Beach defined by high- and low-water mark.

*mark*, the littoral space between being termed the *beach* (Fig. 165). If the coast is precipitous, a beach can only occur in shelving bays and creeks, since elsewhere the tides will rise and fall against a face of rock, as they do on the piers of a port. On such rocky coasts, the line of high-water is sometimes admirably defined by the grey crust of barnacles adhering to the rocks. Sea-weeds likewise indicate the limits of the beach, the large laminarian forms marking the line of low-water. Where the beach is flat, and the rise and fall of the tide great, many square miles of sand or mud may be laid bare in one bay at low-water.

The height of the tide varies from zero up to 60 or 70 feet.[1] It is greatest where, from the form of the land, the tidal wave is cooped up within a narrow inlet or estuary. Under such circumstances the advancing tide sometimes gathers itself into one or more large waves, and rushes furiously up between the converging shores. This is the origin of the "bore" of the Severn, which rises to a height of 9 feet, while the rise and fall of the tide at Chepstow amounts to a maximum of 50 feet.[2] In like manner, the tides which enter the Bay of Fundy, between Nova Scotia and New Brunswick, are more and more cooped up and rise higher as they ascend that strait, till they reach a height of 70

[1] A Committee was appointed by the British Association to investigate the effects of wind and atmospheric pressure on the tides. Its first report appeared in the volume for 1896, pp. 503-526.

[2] On the bore of the Severn, see V. Cornish, *Nature*, lxii. (1900), p. 126; *Geograph. Journ.* 1902, p. 52; C. T. Whitmell, *Nature*, lxv. (1902), p. 344; E. W. Prevost, *op. cit.* pp. 366, 392.

feet.[1] The bore on the Tsien-Tang Kiang, 70 miles from Shanghai, rushes up the estuary as a huge breaker 20 feet or more in height, with a loud roar and a speed of sometimes eight knots an hour.[2]

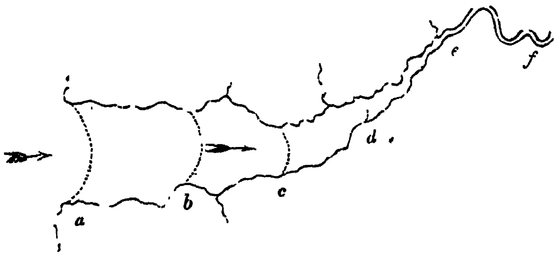



Fig. 166.—Effect of converging shores upon the Tidal Wave (*B.*).
The tidal wave, running up in the direction of the arrows, rises successively higher at *a*, *b*, and *c* to *d*, after which it slackens and dies away at the upper limit of tides, *f*.

While the tidal swelling is increased in height by the shallowness and convergence of the shores between which it moves, it gains at the same time force and rapidity. No longer a mere oscillation or pulsation of the great ocean, the tide acquires a true movement of translation, and gives rise to currents which rush past headlands and through narrows in powerful streams and eddies.

The rocky and intricate navigation of the west of Scotland and Scandinavia furnishes many admirable illustrations of the rapidity of these tidal currents. The famous whirlpool of Corryvreckan, the lurking eddies in the Kyles of Skye, the breakers at the Bore of Duncansby, and the tumultuous tideway, grimly named by the northern fishermen "The Merry Men of Mey," in the Pentland Firth, bear witness to the strength of these sea-rivers. At the last-mentioned strait, the current or "race" at its strongest runs at the rate of 10 miles an hour, which is fully three times the speed of most of our large rivers.

(2) *Currents.*—Modern researches in ocean-temperature have disclosed the remarkable fact that, beneath the surface-layer of water affected by the temperature of the latitude, there lies a vast mass of cold water, the bottom-temperature of every ocean in free communication with the poles being little above, and sometimes actually below, the freezing-point of fresh water.[3] In the North Atlantic, a temperature of 40° Fahr. is reached at an average depth of about 800 fathoms, all beneath that depth

[1] See J. W. Dawson on the tides of the gulf and river of St. Lawrence and Bay of Fundy, *Nature*, lx. (1899), p. 291 (see p. 161); W. H. Wheeler, *op. cit.* p. 461.

[2] Report to the Admiralty by Commander Moore, R.N., 1888.

[3] See, in particular, memoirs by Carpenter and Wyville Thomson, *Proc. Roy. Soc.* xvii. (1868); *Brit. Assoc.* xli. *et seq.*; *Proc. Roy. Geograph. Soc.* xv. Reports to the Admiralty of the *Challenger* Exploring Expedition. Wyville Thomson's 'Depths of the Sea,' 1873, and 'Atlantic,' 1877. Narrative volume of *Challenger Report*. Prince of Monaco, *Brit. Assoc.* 1892. Sir J. Murray, "On the Annual Range of Temperature in the Surface of the Ocean and its Relation to other Oceanographical Phenomena," *Geograph. Journ.* xii. (1898), pp. 118-137; "On the Temperature of the Floor of the Ocean and of the Surface-waters of the Ocean," *op. cit.* xiv. (1899), pp. 34-51.

being progressively colder. In the equatorial parts of that ocean, the same temperature comes to within 300 fathoms of the surface. In the South Atlantic, off Cape of Good Hope, the mass of cold water (below 40°) rises likewise to about 300 fathoms from the surface. This distribution of temperature proves that there must be a transference of cold polar water towards the equator; for in the first place, the temperature of the great mass of the ocean is much lower than that which is normal to each latitude, and in the second place, it is much lower than that of the superficial parts of the earth's crust underneath. On the other hand, the movement of water from the poles to the equator requires a return movement of compensation from the equator to the poles, and this must take place in the superficial strata of the ocean. Apart therefore from those rapid river-like streams which traverse the ocean, and to which the name of Currents is given, there must be a general drift of warm surface-water towards the poles. This is doubtless most markedly the case in the North Atlantic, where, besides the current of the Gulf Stream, there is a prevalent set of the surface-waters towards the north-east. As the distribution of life over the globe is everywhere so dependent upon temperature, it becomes of the highest interest to know that a truly arctic submarine climate exists everywhere in the deeper parts of the sea. With such uniformity of temperature, we may anticipate that the abysmal fauna will be found to possess a corresponding sameness of character, and that arctic types may be met with even on the ocean-bed at the equator.

But besides this general drift or set, a leading part in oceanic circulation is taken by the more defined currents. The tidal wave only becomes one of translation as it passes into shallow water, and is thus of merely local consequence. But a vast body of water, known as the Equatorial Current, moves in a general westerly direction round the globe. Owing to the way in which the continents cross its path, this current is subject to considerable deflections. Thus, that portion which crosses the Atlantic from the African side strikes against the mass of South America, and divides—one portion turning towards the south and skirting the shores of Brazil; the other bending north-westward into the Gulf of Mexico, and issuing thence as the well-known Gulf Stream. This equatorial water is comparatively warm and light. At the same time, the heavier and colder polar water moves towards the equator, sometimes in surface-currents like those which skirt the eastern and western shores of Greenland, but more generally as a cold under-current which creeps over the floor of the ocean even as far as the equator.

A large body of information has now been gathered as to the great marine currents which traverse the upper parts of the ocean, but comparatively little is yet known of the velocity of the movement of the water at great depths. Where the bottom is covered with a deep fine ooze we may infer that the rate of movement must be so feeble as not to disturb the deposition of the finest sediment. Where, on the other hand, "hard-bottom" is found, we may probably conclude that

a sufficiently strong current flows there to prevent the accumulation of sediment, for all over the ocean there is enough of organic and inorganic particles diffused through the water to form a deposit on the floor if the conditions are favourable. A few observations have been made showing that at considerable depths among submarine ridges or islands strong currents exist. At a depth of 3000 feet near Gibraltar the telegraph cable from Falmouth was ground like the edge of a razor; and the scouring effects of strong currents have been noted at depths of 6000 feet between the Canary Islands.[1]

Much discussion has arisen in recent years as to the cause of oceanic circulation. Two rival theories have been given. According to one of these, the circulation entirely arises from that of the air. The trade-winds, blowing from either side of the equator, drive the water before them until the north-east and south-east currents unite in equatorial latitudes into one broad westerly-flowing current. Owing to the form of the land, portions of this main current are deflected into temperate latitudes, and, as a consequence, an equivalent bulk of polar water requires to move towards the equator to restore the equilibrium. According to the other view, the currents arise from differences of temperature (and according to some, of salinity also): the warm and light equatorial water stands at a higher level than the colder and heavier polar water; the former, therefore, flows down as it were pole-wards, while the latter moves as a bottom-inflow towards the equator; the cold bottom-water under the tropics slowly ascends to the warmer upper layers, and rises in temperature towards the surface, whence it drifts away as warm water towards the pole, and, on being cooled down there, descends and begins another journey to the equator. There can be no doubt that the winds are directly the cause of such currents as the Gulf Stream, and therefore, indirectly, of return cold currents from the polar regions. It seems hardly less certain that, to some extent at least, differences of temperature, and therefore of density, must occasion movements in the mass of the oceanic waters.[2]

Apart from disputed questions in physics, the main facts for the geological reader to grasp are—that a system of circulation exists in the ocean; that warm currents move round the equatorial regions, and are turned now to the one side, now to the other, by the form of the continents along and around which they sweep; that cold currents set in from poles to equator; and that, apart from actual currents, there is an extremely slow "creep" of the polar water, under the warmer upper layers, to the equator.

[1] T. M. Reade, *Phil. Mag.* xxv. (1888), p. 342. Some of the "sub-oceanic changes" enumerated by Dr. John Milne in the paper cited on p. 368 are not improbably explicable by the action of such currents.

[2] The student may consult Maury's 'Physical Geography of the Sea,' but more particularly Dr. Carpenter's papers in the *Proceedings of the Royal Society* for 1869-73, and *Journal of the Royal Geographical Society* for 1871-77, on the side of temperature; and Herschel's 'Physical Geography,' and Croll's 'Climate and Time,' on the side of the winds.

(3) *Waves and Ground-Swell.*—A gentle breeze curls into ripples the surface of water over which it blows. A strong gale or furious storm raises the surface into waves. The agitation of the water in a storm is prolonged to a great distance beyond the area of the original disturbance, and then takes the form of the long heaving undulation termed *Ground-swell.* Waves which break upon the land or sunken rocks are called *Breakers*, and the same name is applied to the ground-swell as it bursts into foam and spray upon submarine reefs and shoals. The concussion of earthquakes sometimes gives rise to very disastrous ocean-waves (p. 375).

The height and force of waves depend upon the strength and continuance of the wind, the breadth and depth of sea and height of the tides (in tidal seas), and on the form and direction of the coast-line. The longer the "fetch," and the deeper the water, the higher the waves. A coast directly facing the prevalent wind will have larger waves than a neighbouring shore which presents itself at an angle to the wind or bends round so as to form a leeshore. The highest waves in the narrow British seas probably never exceed 15 or 20 feet, and usually fall short of that amount. The increase of their normal height by the effect of gales varies from 3 to 4 feet, but under exceptional conditions may rise to 5 or even 7 feet.[1] The greatest height observed by Scoresby among the Atlantic waves was 43 feet.[2]

Ground-swell propagated across a broad and deep ocean produces by far the most imposing breakers. So long as the water remains deep and no wind blows, the only trace of the passing ground-swell on the open sea is the huge broad heaving of the surface. But where the water shallows, the superficial part of the swell, travelling faster than the lower, which encounters the friction of the bottom, begins to curl and crest as a huge billow or wall of water, that finally bursts against the shore. Such billows, even when no wind is blowing, often cover the cliffs of the north of Scotland with sheets of water and foam up to heights of 100 or even nearly 200 feet. During north-westerly gales, the windows of the Dunnet Head lighthouse, at a height of upwards of 300 feet above high-water mark, are said to be sometimes broken by stones swept up the cliffs by the sheets of sea-water which then deluge the building.

A single roller of the ground-swell 20 feet high falls, according to Mr. Scott Russell, with a pressure of about a ton on every square foot. The late Mr. Thomas Stevenson conducted a series of measurements of the force of the breakers on the Atlantic and North Sea coasts of Britain. The average force in summer was found in the Atlantic to be 611 lb. per square foot, while in the winter it was 2086 lb., or more than three times as great. On several occasions, both in the Atlantic and North Sea, the winter breakers were found to exert a pressure of three tons per square foot, and at Dunbar as much as three

[1] W. H. Wheeler, *Brit. Assoc.* 1895, and Report of Committee, 1896.

[2] *Brit. Assoc. Rep.* 1850, p. 26; see also V. Cornish, *op. cit.* 1899, p. 636. A table of observed heights of waves round Great Britain is given in T. Stevenson's 'Harbours,' p. 20.

tons and a half.[1] Besides the waves produced by ordinary wind action, others of an extraordinary size and destructive power are occasionally caused by local atmospheric disturbances. Such are probably the *raz de marée* of the French coast, which occasionally rise to a height of several feet, and, where the shores converge inland, do considerable damage. Still more serious are the effects of a violent cyclone-storm. The mere diminution of atmospheric pressure in a cyclone must tend to raise the level of the ocean within the cyclone limits. But the further furious spiral in-rushing of the air towards the centre of the low-pressure area drives the sea onward, and gives rise to a wave or succession of waves having great destructive power. Thus, on 5th October 1864, during a great cyclone which passed over Calcutta, the sea rose in some places 24 feet, and swept everything before it with irresistible force, drowning upwards of 48,000 people.

Besides the height and force of waves, it is important to know the depth to which the sea is affected by such superficial movements. Sir. G. Airy states that ground-swell may break in 100 fathoms water.[2] It is common to find boulders and shingle disturbed at a depth of 10 fathoms, and even driven from that depth to the shore, and waves may be noticed to become muddy from the working-up of the silt at the bottom, where they have reached water of 7 or 8 fathoms in depth.[3] In the English Channel coarse sediment is disturbed at depths of 30 or more fathoms.[4] It is stated by Delesse that engineering operations have shown submarine constructions to be scarcely disturbed at a greater depth than 5 metres (16·4 feet) in the Mediterranean and 8 metres (26·24 feet) in the Atlantic.[5] In the Bay of Gascony, the depth at which the sea breaks and is effective in the transport of sand along the bottom, is said to vary from scarcely 3 metres in ordinary weather to 5 metres in stormy weather, and only exceeds 10 métres (32·8 feet) in great hurricanes. According to Commander Cialdi, the movement of waves may disturb fine sand on the bottom at a depth of 40 metres (131 feet) in the English Channel, 50 metres (164 feet) in the Mediterranean, and 200 metres (656 feet) in the ocean.[6] Off the Florida coast the disturbing action of the waves is believed to cease below 100 fathoms.[7] As above remarked, the probable influence of currents has been detected at much greater depths.

(4) *Ice on the Sea.*—In this place may be most conveniently noticed the origin and movements of the ice which in circumpolar latitudes

[1] T. Stevenson, *Trans. Roy. Soc. Edin.* xvi. p. 25; treatise on 'Harbours,' p. 42.

[2] *Encyclopedia Metropolitana*, art. "Waves." Gentle movement of the bottom water is said to be sometimes indicated by ripple-marks on the fine sand of the sea-floor at a depth of 600 feet.

[3] T. Stevenson's 'Harbours,' p. 15.

[4] A. R. Hunt, *Proc. Roy. Dublin Soc.* iv. (1884), p. 285. For further information on this subject, see *postea*, pp. 576, 581, 582.

[5] 'Lithologie des Mers de France' (1872), p. 110.

[6] Quoted by Delesse, *op. cit.* p. 111.

[7] A. Agassiz, *Amer. Acad.* xii. (1882), p. 108.

covers the sea. This ice is derived from two sources—α, the freezing of the sea itself, and β, the seaward prolongation of land-ice.[1]

α. Three chief types of sea-ice have been observed. (*a*) In the Arctic sounds and bays, the littoral waters freeze along the shores, and form a cake of ice which, upborne by the tide and adhering to the land, is thickened by successive additions below, as well as by snow above, until it forms a shelf of ice 120 to 130 feet broad, and 20 to 30 feet high. This shelf, known as the Ice-foot, serves as a platform on which the

Fig. 167.—Disrupted Floe-ice of Arctic Seas.

abundant débris, loosened by the severe frosts of an arctic winter, gathers at the foot of the cliffs. It is more or less completely broken up in summer, but forms again with the early frosts of the ensuing autumn. (*b*) The surface of the open sea likewise freezes over into a continuous solid sheet, which, when undisturbed, becomes in the arctic regions about eight feet thick, but which in summer breaks up into separate masses, sometimes of large extent, and is apt to be piled up into huge, irregular heaps (Fig. 167). This is what navigators term Floe-ice, and the separate floating cakes are known as *floes*. Ships fixed among these

[1] Consult on the whole of this subject K. Weyprecht's 'Die Metamorphosen des Polareises,' Vienna, 1879; Payer's 'New Lands within the Arctic Circle,' 1876, chap. i. The physics of sea-ice are discussed by O. Pettersson, 'Vega-expeditionens Vetenskapliga Iakttagelser,' ii. p. 290, Stockholm, 1883. Much information about the floe-ice and the Greenland icebergs at their birthplace will be found in Drygalski's volumes cited on p. 535, and in the papers of Professor Chamberlin in the *Journ. Geol.* See also a paper by R. S. Tarr on "Arctic Sea-ice as a Geological Agent," *Amer. Journ. Sci.* iii. (1897), p. 223.

floes have drifted with the ice for hundreds of miles, until at last liberated by its disruption. (*c*) In the Baltic Sea, off the coast of Labrador and elsewhere, ice has been observed to form on the sea-bottom. It is known as Ground-ice or Anchor-ice. In the Labrador fishing-

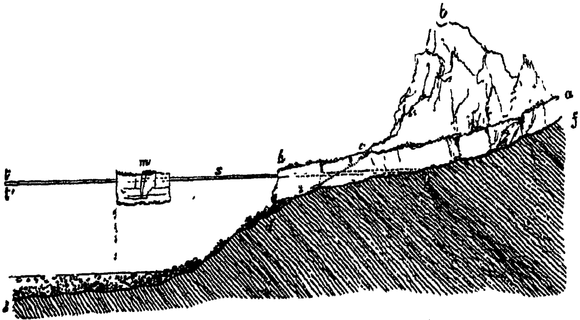


Fig. 168.—Formation of Icebergs (*B.*).

The glacier (*a*, *h*) descends from mountainous ground (*b*) to the sea-level (*s*), bearing moraine-stuff on the surface, pushing on detritus below (*d*), and sending off icebergs (*m*), which may carry detritus and drop it over the sea-bottom; *t*, *t'*, *g*, lines of high and low water.

grounds, it forms even at considerable depths. Seals caught in the lines at those depths are said to be brought up sometimes solidly frozen.[1]

β. In the Arctic regions, vast glaciers drain the snow-fields, and, descending to the sea, extend for some distance from shore until large fragments break off and, under the influence of the prevalent off-shore winds, float away seawards (Fig. 168). These detached masses are Ice-

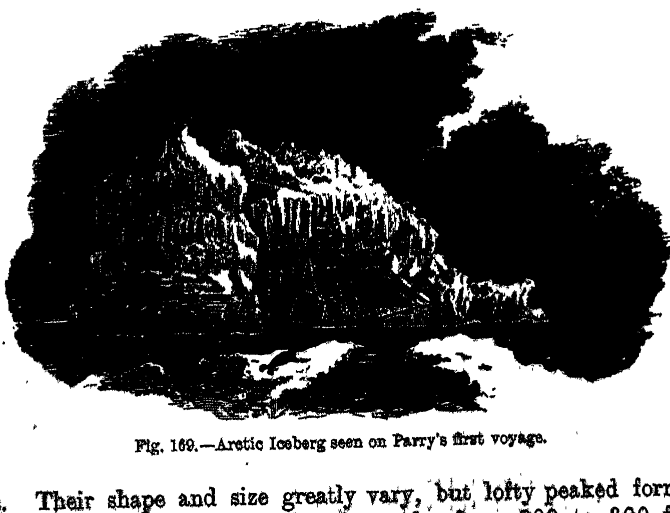


Fig. 169.—Arctic Iceberg seen on Parry's first voyage.

bergs. Their shape and size greatly vary, but lofty peaked forms are common (Fig. 169), and they sometimes rise from 200 to 300 feet or

[1] See H. Y. Hind, *Canadian Naturalist*, viii. (1878), pp. 227, 262.

more above the level of the sea.[1] As the part that appears above water is only about one-ninth of the whole mass of ice, these larger bergs may sometimes be from 1800 to 2700 feet thick from base to top, though the submarine part of the ice may be as irregular in form and thickness as the portion above water.[2] Icebergs of the largest size consequently require water of some depth to float them, but are often seen aground before they have been able to reach the deeper sea outside. In the antarctic regions, where one vast sheet of ice envelops the land and protrudes into the sea as a long, lofty rampart of ice, the detached icebergs often reach a great size, and are characterised by the frequency of a flat tabular form (Fig. 170).[3]

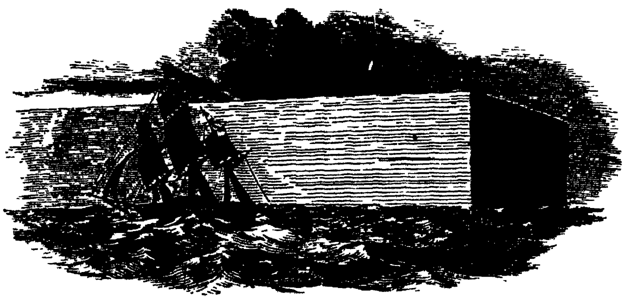


Fig. 170.—Tabular Iceberg detached from the great Antarctic Ice-barrier. (Wilkes.)

II. **Geological Work.**—(1) Influence on Climate.—Were there no agencies in nature for distributing temperature, there would be a regular and uniform diminution of the mean annual temperature from equator to poles, and the *isothermal* lines, or lines of equal heat, would coincide with lines of latitude. But no such general correspondence actually exists. A chart of the globe, with the isothermal lines drawn across it, shows that their divergences from the parallels are striking, and most so where they approach and cross the ocean. Currents from warm regions raise the temperature of the tracts into which they flow; those from cold regions lower it. The ocean, in short, is the great distributor of temperature over the globe.

As an illustration, the two opposite sides of the North Atlantic may be taken. The cold arctic current, flowing southward along the north-east coast of America, reduces the mean annual temperature of that region. On the other hand, the Gulf Stream and surface-drift bring to the shores of the north-west of Europe a temperature much above what these would otherwise enjoy. Dublin and the south-eastern headlands of Labrador lie on the same parallel of latitude, yet differ as much as 18° in their mean annual temperature, that of Dublin being 50°, and that of Labrador 32° Fahr. Croll

[1] Drygalski found the icebergs shed by the great Jacobshaven ice-field in North Greenland to range in height from 21 to 137 or perhaps even 195 metres (69 to 450 or 639 English feet); *op. supra cit.* chap. xiv. Salisbury, *Journ. Geol.* iii. pp. 81, 92.

[2] On flotation of icebergs, see *Geol. Mag.* (2nd sec.), iii. pp. 303, 379; iv. 65, p. 135.

[3] On antarctic icebergs, see Arctowski, *Geogr. Journ.* July 1899; *Compt. rend.* cxxxii. (1901), p. 725.

estimated that the Gulf Stream conveys nearly half as much heat from the tropics as is received from the sun by the entire arctic regions.[1]

(2) Erosion. A. *Chemical.*—The chemical action of the sea upon the rocks of its bed and shores has not yet received the close observation and experimental treatment which it deserves.[2] It is evident, however, that changes analogous to those effected by fresh water on the land must be in progress. Oxidation, solution, and the formation of carbonates, no doubt continually take place. The solvent action of sea-water is most conspicuously shown among the calcareous rocks of tropical seas. Sir John Murray first called attention to this solution as evinced in the sheltered waters of the lagoons of coral islands,[3] and his observations have since been confirmed and extended by Professor A. Agassiz, who has brought forward numerous illustrations of the way in which the lower part of limestone cliffs is eaten away and isolated rocks are reduced to mushroom shapes.[4]

The experiments which have been made to determine the nature and amount of the chemical action of sea-water have thrown some little light on this subject. Sir John Murray, who had shown that calcareous organisms gradually disappear from the deposits of the sea-bottom as these are traced down into the abysses, explained their absence there by the influence of the water containing carbonic acid in dissolving the lime. Subsequently he conducted a series of experiments to demonstrate the truth of this view. Ten specimens of coral of different species were immersed in sea-water and allowed to remain for periods varying from 20 to 60 days. In each case a perceptible loss of material took place, varying from 0·0725 to 0·1707 of their weight, which he estimated to be equal to a rate of loss amounting to from 0·453 to 0·1860 from one square inch of surface in a year. The more areolar or amorphous corals were attacked more rapidly than the harder crystalline varieties.[5]

We may judge, indeed, of the nature and rapidity of some of these changes by watching the decay of stones and material employed in the construction of piers. Mr. Mallet—as the result of experiments with specimens sunk in the sea—concluded that from $\frac{3}{10}$ to $\frac{4}{10}$ of an inch in depth in iron castings 1 inch thick, and about $\frac{6}{10}$ of an inch of wrought-iron, will be destroyed in a century in clear salt water. Mr. Stevenson, in referring to these experiments, remarks that at the Bell Rock lighthouse, twenty-five

[1] See a series of papers by him on the "Gulf Stream and Ocean Currents," in *Geol. Mag.* and *Phil. Mag.* for 1869, 1870-74, and his work 'Climate and Time'; likewise a series of controversial papers on this subject by him and Professor Newcombe, *Phil. Mag.* 1883-84. Professor Haughton offered some calculations of the actual amount of influence exercised by ocean-currents upon climate, and of the effect of a current between the Indian and Arctic Oceans across Mesopotamia and the Aralo-Caspian depression. *Brit. Assoc.* 1881, Reports, pp. 451, 463. Agassiz on Gulf Stream in his 'Three Cruises of the *Blake*,' i. p. 241.

[2] See Bischof's 'Chemical Geology,' vol. i. chap. vii.; Daubrée, 'Geol. expérim.' vol. i. The subject has recently been undertaken by Professor Joly of Dublin, and from his skilled hands some valuable results may be anticipated. See his first paper in *Compt. rend. Congrès Géol. Internat. Paris*, 1900, p. 774, and *Brit. Assoc.* 1900, p. 731.

[3] *Proc. Roy. Soc. Edin.* 1880, p. 505.

[4] "The Coral-reefs of the Hawaiian Islands," *Bull. Mus. Comp. Zool. Harvard*, xvii. No. 3, pp. 125, 128; "A Visit to the Bermudas in March 1894," *op. cit.* xxvii. No. 2, p. 215; "The Elevated Reef of Florida," *op. cit.* xxviii. (1896), p. 39.

[5] *Proc. Roy. Soc. Edin.* xvii. (1889), p. 109. See also R. Irvine, *Nature*, 1888, p. 461; J. G. Ross, *ibid.* p. 162. Compare A. Agassiz, *Bull. Mus. Comp. Zool. Harvard*, xvii. No. 3 (1889), p. 125.

different kinds and combinations of iron were exposed to the action of the sea, and all yielded to corrosion. In some of these castings, the loss was at the rate of an inch in a century. "One of the bars which was free from air-holes had its specific gravity reduced to 5·63, and its tranverse strength from 7409 lb. to 4797 lb., and yet presented no external appearance of decay. Another apparently sound specimen was reduced in strength from 4068 lb. to 2352 lb., having lost nearly half its strength in fifty years."[1] Similar results were observed by Mr. Grothe, resident engineer at the construction of the ill-fated railway bridge across the Firth of Tay. A cast iron cylinder (such as was employed in constructing the concrete basements for the piers), which had been below water for only sixteen months, was found to be so corroded that a pen-knife could be stuck through it in many places. An examination of the shore will sometimes reveal a good deal of quiet chemical change on the outer crust of wave-washed rocks. Basalt, for instance, has its felspar decomposed, and shows the presence of carbonates by effervescing briskly with acid. The augite is occasionally replaced by ferrous carbonate. In the experiments recently conducted by Professor Joly, specimens of basalt, orthoclase, obsidian and hornblende reduced to fine powder were kept for three months in a vessel of sea-water through which a current of air passed, so as to maintain the sediment in suspension. He found that the silicates, especially those of the basalt, had lost small but perceptible amounts of silica and lime, and he calculated that this loss in the case of the basalt amounted to rather more than half a gramme per square metre in a year.[2]

The complex chemical changes that take place in the sea through the operation of living and dead organisms are referred to on pp. 605, 611, 621, 624-628.

B. *Mechanical.*—It is mainly by its mechanical action that the sea accomplishes its erosive work. This can only take place where the water is in motion, and, other things being equal, is greatest where the motion is strongest. Hence we cannot suppose that erosion to any appreciable extent can be effected in the abysses of the sea, where the only motion is probably the slow creeping of the polar water. But where the currents are powerful enough to move grains of sand and gravel, a slow erosion may take place even at considerable depths. It is in the upper portions of the sea, however—the region of currents, tides, and waves,—that mechanical erosion is chiefly performed. The depth to which the influence of waves and ground-swell may extend seems to vary greatly according to the situation (*ante*, p. 562). A good test for the absence of serious abrasion is furnished by the presence of fine mud on the bottom. Wherever that is found, we may be tolerably sure that the bottom at that place lies beyond the reach of ordinary breaker-action.[3] From the superior limit of the accumulation of mud up to high-water mark, and in exposed places up to 100 feet or more above high-water mark, lies the zone within which the sea does its work of abrasion. To this zone, even where the breakers are heaviest, a greater extreme vertical range can hardly be assigned than 300 feet, and in most cases it probably falls far short of that extent.

The mechanical work of erosion by the sea is done in six ways.

(i.) The enormous force of the breakers suffices to tear off fragments of the solid rocks.

Abundant examples are furnished by the precipitous shores of Caithness, and of the Orkney and Shetland Islands. It sometimes happens that demonstration of the height

[1] T. Stevenson's 'Harbours,' p. 47. [2] *Op. supra cit.* p. 780.
[3] T. Stevenson, *op. cit.* p. 15.

to which the effective force of breakers may reach is furnished at lighthouses built on exposed parts of the coast. Thus, at Unst, the most northerly point of Shetland, walls were overthrown and a door was broken open at a height of 196 feet above the sea. At the Bishop Rock lighthouse, on the west of England, a bell weighing 3 cwt. was wrenched off at a level of 100 feet above high-water mark.[1] Some of the most remarkable instances of the power of breakers were observed by Mr. Stevenson among the islands of the Shetland group. On the Bound Skerry he found that blocks of rock, up to 9½ tons in weight, had been washed together at a height of nearly 60 feet above the sea; that blocks weighing from 6 to 13½ tons had been actually quarried out of their original bed, at a height of from 70 to 75 feet; and that a block of nearly 8 tons had been driven before the waves, at the level of 20 feet above the sea, over very rough ground, to a distance of 73 feet. He likewise records the moving of a 50-ton block by the waves at Barrahead, in the Hebrides.[2] At Plymouth, also, blocks of several tons in weight have been known to be washed about the breakwater like pebbles.[3]

(ii.) The alternate compression and expansion of air in crevices of rocks exposed to heavy breakers dislocate large masses of stone, even above the direct reach of the waves. It is a fact familiar to engineers that, even from a vertical and apparently perfectly solid wall of well-built masonry exposed to heavy seas, stones will sometimes be started out of their places, and that when this happens, a rapid enlargement of the cavity may be effected, as if the walls were breached by a severe bombardment. At the Eddystone lighthouse, during a storm in 1840, a door which had been securely fastened against the force of the surf from without, was actually driven outward by a pressure acting from within the tower, in spite of the strong bolts and hinges, which were broken. We may infer that, by the sudden sinking of a mass of water hurled against the building, a partial vacuum was formed, and that the air inside forced out the door in its efforts to restore the equilibrium.[4] This explanation may partly account for the way in which the stones are started from their places in a solidly built sea-wall. But besides this cause, we must also consider a perhaps still more effective one in the condensation of the air driven before the wave between the joints and crevices of the stones, and its subsequent instantaneous expansion when the wave drops. During gales, when large waves are driven to shore, many tons of water

[1] T. Stevenson, *op. cit.* p. 31. D. A. Stevenson, *Min. Proc. Inst. Civ. Engin.* xlvi. (1876), p. 7.

[2] T. Stevenson, *op. cit.* pp. 21-37.

[3] The student will bear in mind that the relative weight of bodies is greatly reduced when in water, and still more in sea-water The following examples will illustrate this fact (T. Stevenson's 'Harbours,' p. 107):—

| —— | Specific Gravity. | No. of cubic feet to a ton in air. | No. of feet to a ton in sea-water of specific gravity 1·028. |
|---|---|---|---|
| Basalt . . . . . | 2·99 | 11·9 | 18·26 |
| Red granite . . . | 2·71 | 13·2 | 21·30 |
| Sandstone . . . . | 2·41 | 14·8 | 26·00 |
| Cannel Coal . . . | 1·54 | 23·3 | 70·00 |

[4] Walker, *Proc. Inst. Civ. Engin.* i. p. 15; Stevenson's 'Harbours,' p 10.

are poured suddenly into a cleft or cavern. These volumes of water, as they rush in, compress the air into every joint and pore of the rock at the further end, and then, quickly retiring, exert such a suction as from time to time to bring down part of the walls or roof. The sea may thus gradually form an inland passage for itself to the surface above, in a "blow-hole," or "puffing-hole," through which spouts of foam and spray are in storms shot high into the air.

On the more exposed portions of the west coast of Ireland, and on the north coast of Cornwall, numerous examples of such blow-holes occur. In Scotland, likewise, they may often be observed, as in the Bullers (boilers) of Buchan on the coast of Aberdeenshire, and the Geary Pot near Arbroath. Magnificent instances occur among the Orkney and Shetland Islands, some of the more shattered rocks of these northern coasts being, as it were, honeycombed by sea-tunnels, many of which open up into the middle of fields or moors.

(iii.) The hydraulic pressure of those portions of large waves that enter fissures and passages tends to force asunder masses of rock. The sea-water which, as part of an inrushing wave, fills the gullies and chinks of the shore-rocks, exerts the same pressure upon the walls between which it is confined as the rest of the wave is doing upon the face of the cliff. Each cleft so circumstanced becomes a kind of hydraulic press, the potency of which is to be measured by the force with which the waves fall upon the rocks outside—a force which often amounts to three tons on the square foot. There can be little doubt that by this means considerable pieces of a cliff are from time to time dislodged.

(iv.) The waves make use of the loose detritus within their reach to break down cliffs exposed to their fury. Probably by far the largest amount of erosion is thus accomplished. The blows dealt against shore-cliffs by boulders, gravel and sand swung forward by breakers, were aptly compared by Playfair to a kind of artillery.[1] During a storm upon a shingly coast we may hear, at a distance of several miles, the grind of the stones upon each other, as they are dragged back by the recoil of the waves which had launched them forward.[2] In this tear and wear, the loose stones are ground smaller, and acquire the smooth round form so characteristic of a surf-beaten beach. At the same time, they bruise and wear down cliffs against which they are driven. A rock, much jointed, or from any cause presenting less resistance to attack, is excavated into gullies, creeks and caves; its harder parts standing out as promontories are pierced; gradually a series of detached buttresses and sea-stacks appears as the cliff recedes, and these in turn are wasted until they become mere skerries and sunken surf-beaten reefs (Fig. 171). The surface of the beach is likewise ground down. The reality of this erosion and consequent lowering of level is sometimes instructively displayed where a block of harder rock serves for a time to protect the portion of rocky beach lying beneath it. The block by degrees comes to rest on a growing pedestal,

[1] 'Illustrations of the Huttonian Theory,' sec. 97.

[2] For a graphic account of the heavy roll of the boulders and thundering of the billows as heard in a mine under the sea during a storm, see J. W. Henwood, *Trans. Roy. Geol. Soc. Cornwall*, v. p. 11.

which is eventually cut round by the waves, until the overlying mass, losing its support, rolls down upon the beach. Thereafter the same

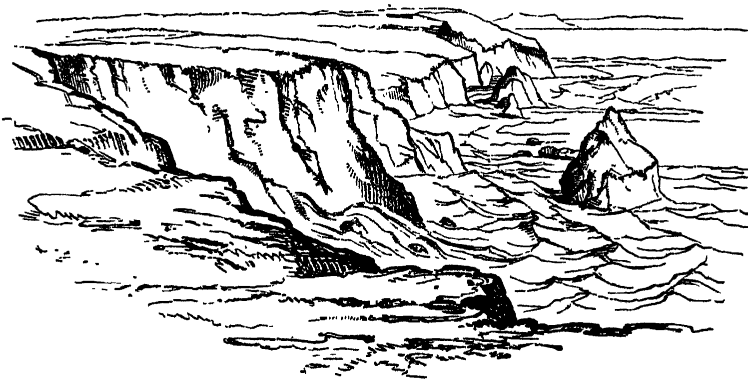


Fig. 171.—Coast of Cornwall, at Bedruthan (Devonian Rocks), cut by the sea into cliffs, bays and stacks (*B.*).

process is renewed, and the boulder itself gradually diminishes in size (Fig. 172).[1]

Fig. 172.—Boulder of Dolerite protecting the portion of volcanic tuff on the beach underneath it; Largo, Fife.

Of the progress of marine erosion, the more exposed parts of the British coast-line furnish many admirable examples. The sea-board of Cornwall presents a most impressive range of cliffs, sea-stacks, caves, gullies, tunnels, reefs and skerries, showing every stage in the process of demolition (Fig. 171). The west coast of Ireland, exposed to the full

[1] See on the action of waves on sea-beaches and sea-bottoms, A. R. Hunt, *Proc. Roy. Dublin Soc.* 1884, p. 241. Other examples from the same locality figured in Fig. 172 are given in the Geological Survey Memoir on Eastern Fife, 1902.

swell of the Atlantic, is in innumerable localities completely undermined by caverns, into which the sea enters from both sides. The precipitous coasts of Skye, Sutherland, Caithness, Aberdeen, Kincardine and Forfar abound in the most impressive lessons of the waste of a rocky sea-margin; while the same picturesque features are prolonged into the Orkney and Shetland Islands, the magnificent cliffs of Hoy towering as a vast wall some 1200 feet above the Atlantic breakers, which are tunnelling and fretting their base.

If such is the progress of waste where the materials consist of the most solid rocks, we may expect to meet with still more impressive proofs of decay where the coast-line can oppose only soft sand or clay to the march of the breakers. Again, the geological student in Britain can examine for himself many illustrations of this kind of destruction around the shores of these islands. Within the last few hundred years entire parishes, with their farms and villages, have been washed away, and the tide now ebbs and flows over districts which in old times were cultivated fields and cheerful hamlets. The coast of Yorkshire between Flamborough Head and the mouth of the Humber, and also that between the Wash and the mouth of the Thames, suffer at a specially rapid rate, for the cliffs in these parts consist in great measure of soft clay. In some places between Spurn Point and Flamborough Head this loss is said to amount to five yards

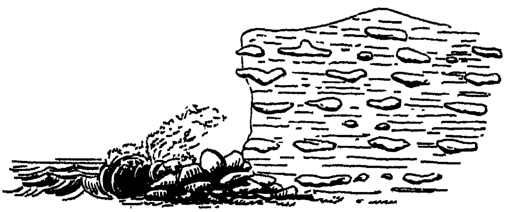


Fig. 178.—Cliffs of clay full of septarian nodules, the accumulation of which serves to arrest the progress of the waves.

per annum.[1] In the forty miles of cliff between Bridlington and Kilnsea the average annual loss is computed at 2¼ yards, which is equal to about one acre for each mile of coast.[2]

Other parts of the European sea-board likewise furnish instructive lessons as to the progress of marine erosion. The destruction of Heligoland, in the North Sea, has been continuous for centuries, the stages in the disappearance of this island being easily followed on the charts of successive periods.[3] Even the hard crystalline rocks of Scandinavia are unable wholly to withstand the assaults of the Atlantic breakers.[4]

While investigating the progress of waste along a coast-line, the geologist has to consider the varying powers of resistance possessed by rocks, and the extent to which the action of the waves is assisted by that of the subaerial agents. Rocks of little tenacity,

[1] R. Pickwell, *Proc. Inst. Civ. Engin.* li. p. 191. On the waste of the coast between the Thames and Wash, see J. B. Redman, *op. cit.* xxiii. (1864), p. 186; C. Reid, *Geol. Mag.* 2nd dec. iv. p. 136. "Geology of Holderness," *Mem. Geol. Surv.* 1885. The Reports of the British Association Committee on the erosion of the sea-coasts of England, 1885-95, give much interesting information on this subject. On the waste of the coast at Southwold and Covehithe, see J. Spiller, *Geol. Mag.* 1896, p. 23; on that at Wirral, G. H. Morton, *op. cit.* p. 516; on that of County Down, *op. cit.* 1897, p. 62.

[2] W. H. Wheeler, 'The Sea Coast,' 1902, p. 2. This volume gives a large amount of information regarding the coasts of England and Northern France.

[3] K. W. M. Wiebel's 'Die Insel Helgoland,' 4to, Hamburg, 1848. The rate of erosion in Holland is referred to in *Nature*, lx. (1899), p. 115.

[4] H. Reusch, *Neues Jahrb.* 1879, p. 244.

and readily susceptible of disintegration, obviously present least resistance to the advance of the waves. A clay, for example, is readily eaten away. If, however, it should contain numerous hard nodules or imbedded boulders, these, as they drop out, may accumulate in front beneath the cliff, and serve as a partial breakwater against the waves (Fig. 173). On the other hand, a hard band or boss of rock may withstand the destruction which overtakes the softer or more jointed surrounding portions, and may consequently be left projecting into the sea, as a line of headland or promontory, or rising as an isolated stack (Fig. 171). Besides mere hardness or softness, the geological structure of the rocks powerfully influences the nature and rate of the encroachment of the sea. Where, owing to the inclination of bedding, joints, or other divisional planes, sheets of rock slope down into the water, they serve as a kind of natural breakwater, up and down

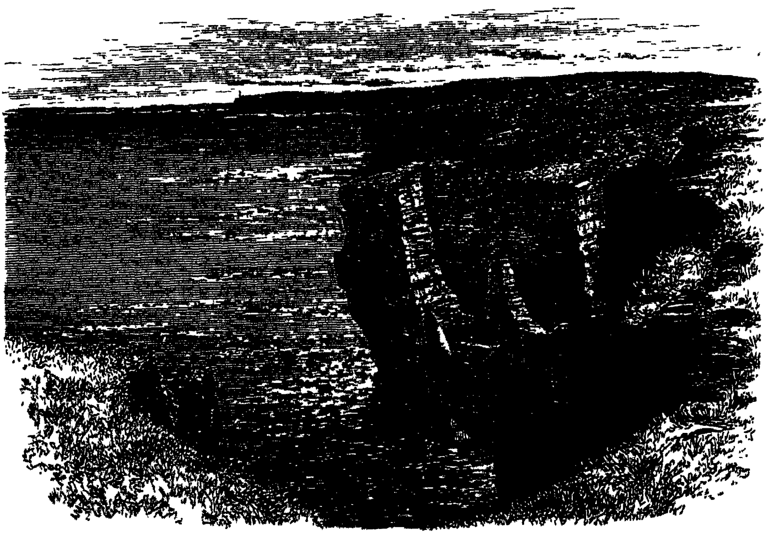


Fig. 174.—Sea-cliffs of flagstone cut along vertical joint-faces, near Holburn Head Caithness.

which the surges rise and fall during calms, or rush in crested billows during gales, the abrasion being here reduced to the smallest proportions. In no part of the degradation of the land, indeed, can the dominant influence of rock-structure be more conspicuously observed and instructively studied than along sea-cliffs. Where the lines of precipice are abrupt, with numerous projecting and retiring vertical walls, it will almost invariably be found that these perpendicular faces have been cut open along lines of intersecting joint. The existence of such lines of division permits a steep or vertical front to be presented by the land to the sea, because, as slice after slice is removed, each freshly bared surface is still defined by a joint-plane (see p. 659).

During the study of any rocky coast where these features are exhibited, the observer will soon perceive that the encroachment of the sea upon the land is not due merely to the action of the waves, but that, even on shores where the gales are fiercest and the breakers most vigorous, the demolition of the cliffs depends largely upon the sapping influence of rain, springs, frosts, and general atmospheric disintegration. In Fig. 174, for example, which gives a view of a portion of the northern Caithness coast, exposed to the full fury of the gales and rapid tidal currents which rush from the Atlantic through the Pentland Firth, we see at once that though the base of the cliff is scooped out by the restless surge into long twilight caves, nevertheless the recession of the precipice is caused by the wedging off of slice after slice, along lines of vertical joints, and that this

process begins at the top, where the subaerial forces and not the waves are the sculptors. Undoubtedly the sea plays its part by removing the materials dislodged, and preventing them from accumulating against and protecting the face of the precipice. But were it not for the potent influence of subaerial decay, the progress of the sea would be

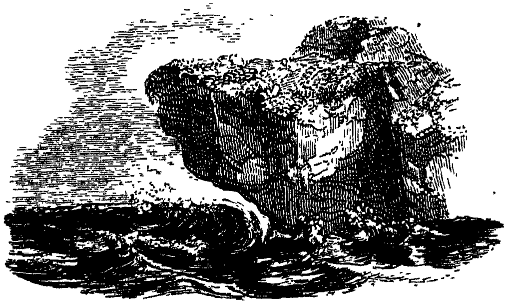


Fig. 175.—Marine erosion, where exceptionally the base of a cliff recedes faster than the upper part.

comparatively feeble. The very blocks of stone which give the waves so much of their efficacy as abrading agents, are in great measure furnished to them by the action of the meteoric agents. If sea-cliffs were mainly due to the destructive effects of the waves, they ought to overhang their base, for only at or near their base does the sea act (Fig. 175). But the fact that, in the vast majority of cases, sea-cliffs, instead of overhanging,

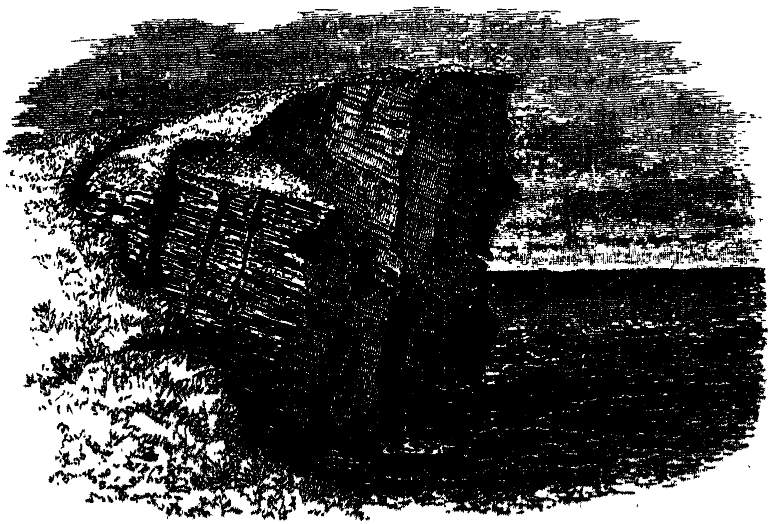


Fig. 176.—Overhanging cliff, Brough of Birsa, Orkney, due to landward inclination of joints.

slope backward, at a greater or less angle, from the sea (Fig. 171), shows that the waste from subaerial action is really greater than that from the action of the breakers.[1] Even when a cliff actually overhangs, however, it may often be shown that the apparent greater recession of its base, and inferentially the more powerful denuding action of the sea, are deceptive. In Fig. 176, one of the innumerable examples from the Old Red

[1] Whitaker, *Geol. Mag.* iv. p. 447.

Sandstone cliffs of Caithness and the Orkney and Shetland Islands, we at once perceive that the process of demolition is precisely similar to that already cited in Fig. 174. The cliff recedes by the loss of successive slices from its sea-front, which are wedged off not by the waves below, but by the subaerial agents above, along lines of parallel joint. To the inclination of these divisional planes at a high angle from the sea, the precipice owes its slope towards the land.

(v.) *Tidal Erosion.*—Probably the chief erosive influence of the tides is indirect, where the tidal waves, by raising the general surface of the water, enable wind-waves to act with effect on a greater area of land. As already remarked, these waves during gales in the British seas may be increased several feet above their normal height. Reference has been made (pp. 560, 562) to the existence of currents at considerable depths in the ocean, though not in the profounder abysses. These movements have been observed in straits between islands or submarine ridges, and they are doubtless connected with the tidal wave. They seem to possess sufficient scour to prevent the accumulation of sediment; but whether they are effective in eroding hollows on the sea-floor, as has been claimed for them, may be doubted. Their power to dig out hollows or to deepen and widen channels must depend not merely on their velocity but upon the presence of detritus which they can use in abrasion, for without this detritus they could not remove the surface of hard rocks.[1]

(vi.) *Ice-erosion.*—Among the erosive operations of the sea must be included what is performed by floating ice. Along the margin of arctic lands, the ice formed along the shores shields them from attacks by the waves, and even when broken up as the season advances the dislodged floes break the force of the waves and thus continue to exercise a protective influence.[2] Nevertheless, a good deal is done by the disrupted floe-ice and ice-foot, both in abrasion and in deposit. Cakes of ice, driven by storms, tear up and redistribute the soft shallow-water or littoral deposits, rub and scratch the rocks, and push gravel and blocks of rock before them as they strand on the shore. Hence beaches of coarse shingle and large boulders may be formed by the stranding ice, though the sea-bottom immediately below may be covered with fine mud. The constant stranding and rasping of the floe-ice prevents the growth of a continuous coating of sea-weed, barnacles, &c., which would so far protect the shore-rocks from abrasion. Icebergs, when they are produced by the "calving" of huge masses from the surface of a glacier, give rise to waves sometimes of considerable size, whereby the shores are more vigorously eroded. At the time of their detachment or in their subsequent re-adjustments in consequence of melting, they from time to time thump heavily on the bottom, stirring up the mud and causing much destruction of life on the sea-floor. As they are driven before a gale they acquire great momentum, and must doubtless grind down any submarine rock on which they grate as they are driven along. The geological operations

[1] The potency of tidal action has been long maintained by Mr. T. Mellard Reade, *Proc. Geol. Soc. Liverpool*, 1873; *Phil. Mag.* xxv. (1888), p. 338.

[2] R. S. Tarr, *Amer. Jour. Sci.* iii. (1897), p. 224.

of floating ice were formerly invoked by geologists to explain much that is now believed to have been entirely the work of ice on land.[1] The general system of ice-striation on the rocks of glaciated countries points to the radiation of the striating agent from centres, to a continuity of operation along definite lines, and to a capacity for moulding itself to the details of the topography, which would be possessed by ice-sheets and glaciers, but are inconceivable in the case of masses of floating ice driven about at the mercy of winds and currents, altogether irrespective of the form of the sea-bottom.

(3) Transport.—By means of its currents the sea transports mechanically-suspended sediment to varying distances from the land. The distance will depend on the size, form and specific gravity of the sediment on the one hand, and on the velocity and transporting power of the marine current on the other. Babbage estimated that if, from the mouth of a river 100 feet deep, suspended limestone mud, of different degrees of fineness, were discharged into a sea having a uniform depth of 1000 feet over a great extent, four varieties of silt, falling respectively through 10, 8, 5 and 4 feet of water per hour, would be distributed as in the following table:[2]—

| No. | Velocity of fall per hour. | Nearest distance of deposit to river. | Length of deposit. | Greatest distance of deposit from river. |
|---|---|---|---|---|
| | feet. | miles. | miles. | miles. |
| 1 | 10 | 180 | 20 | 200 |
| 2 | 8 | 225 | 25 | 250 |
| 3 | 5 | 360 | 40 | 400 |
| 4 | 4 | 450 | 50 | 500 |

It must be borne in mind, however, that mechanical sediment sinks faster in salt than in fresh water.[3] The chief part of the fine mud in the layer of river-water, which floats for a time on the salter and heavier sea-water, sinks to the bottom as soon as the two waters commingle. It has been ascertained, nevertheless, by direct observation that an appreciable amount of extremely fine clay is present in ocean-water even far away from land, the proportion so transported depending not only on the size and weight of the particles, but on the temperature and to a less extent on the salinity, being greater the lower the temperature and salinity. In specimens of surface-water taken from various oceans the amount of mechanically suspended silicates (clay) was found to be as follows:[4]—

[1] For an account of the work of floating ice ("pan-ice"), see H. Y. Hind, *Canadian Naturalist*, vii. (1878), p. 229.

[2] *Q. J. Geol. Soc.* xii. p. 368.

[3] See *ante*, pp. 491, 511, and authorities there cited.

[4] Murray and Irvine, *Proc. Roy. Soc. Edin.* xviii. (1891), p. 243. These authors regard the silicates thus mechanically suspended in sea-water as the probable source of most of the silica secreted by marine plants and animals (*postea*, p. 625).

| | In 14 litres of water. | | Per cubic mile of water. |
|---|---|---|---|
| Atlantic Ocean, lat. 51° 20′, long. 31° W. | 0·0052 grm. | = | 1604 tons |
| German Ocean, 30 miles E. of May Island | 0·0063 ,, | = | 1946 ,, |
| Mediterranean, centre of Eastern basin . | 0·0065 ,, | = | 2031 ,, |
| Baltic Sea, salinity 1005·5 . . . . | 0·0105 ,, | = | 3200 ,, |
| Red Sea, off Brothers Island . . . . | 0·0006 ,, | = | 264 ,, |
| Indian Ocean, lat. 15° 46′ N., long. 58° 51′ E. | 0·0006 ,, | = | 264 ,, |

Near the land, where the movements of the water are active, much coarse detritus is transported along-shore or swept farther out to sea. A prevalent wind, by creating a current in a given direction, or a strong tidal current setting along a coast-line, will cause the shingle to travel coastwise, the stones getting more and more rounded and reduced in size as they recede from their source. In tidal seas such as those around the British Isles the prevalent drift of the littoral detritus is on the whole in the direction of the flow of the flood-tide, though liable to local deviations according to the form of the coast-line.[1] The Chesil Bank, which runs as a natural breakwater 16 miles long, connecting the Isle of Portland with the mainland of Dorsetshire, consists of drifted rounded shingle.[2] On the Moray Firth, the reefs of quartz-rock about Cullen furnish abundance of shingle, which, urged by successive easterly gales, moves westwards along the coast for more than 15 miles. The coarser sediment probably seldom goes much beyond the littoral zone. Returning to the subject of the depth to which wave-action extends (*ante*, p. 562), we may take note that it has been observed by the fishermen at Land's End that their lobster-pots are often filled with coarse sand and shingle in depths up to 30 fathoms during heavy ground-swells, and that some of the stones weigh as much as one pound.[3] From a depth of even 600 fathoms in the North Atlantic, between the Faroe Islands and Scotland, small pebbles of volcanic and other rocks are dredged up which may have been carried by an arctic under-current from the north. Sir John Murray and Captain Tizzard, however, have brought up large blocks of rounded shingle from that bank at a depth of 300 fathoms. Such detritus can hardly be due to any present action of the sea, for at these depths the force of currents at the bottom is probably too feeble to push along coarse shingle. It may be moraine-stuff dating back to the ice-sheets of the Glacial period, its finer particles having been swept away, while it is prevented from being buried under submarine mud by the scour of the currents over the bank. Blocks of stone brought up

[1] W. H. Wheeler, 'The Sea-Coast,' p. 73.

[2] On the Chesil Bank, see J. Coode, *Min. Proc. Inst. Civ. Engin.* xii. p. 520. J. B. Redman, *op. cit.* xi. p. 201; xxiii. p. 226; *Nature*, xxvi. pp. 30, 104, 150; Prestwich, *Min. Proc. Inst. Civ. Engin.* xl. (1875), p. 115; H. W. Bristow and W. Whitaker, *Geol. Mag.* vi. (1869), p. 433; O. Fisher, *op. cit.* 1874, p. 285; G. H. Kinahan, *op. cit.* 1874; *Min. Proc. Inst. Civ. Engin.* lviii. (1878); A. R. Hunt, *Proc. Roy. Dublin Soc.* iv. (1884), p. 241; V. Cornish, *Proc. Dorset Nat. Hist. Field-Club*, 1898, also *Geog. Journ.* May 1898; W. H. Wheeler, 'The Sea-Coast,' 1902, p. 144. The general transport of littoral detritus in the English Channel is from west to east; Sir J. Prestwich, however, thought that at the Chesil Bank this direction is locally reversed.

[3] J. N. Douglas, *Min. Proc. Inst. Civ. Engin.* xl. (1875), p. 793.

from depths of more than 2000 fathoms in the Atlantic (lat. 49° N., long. 43°-44° W.) have probably been dropped by icebergs from the north.[1]

Much fine sediment is visibly carried in suspension by the sea for long distances from land. The Amazon pours so much silt into the sea as to discolour it for several hundred miles. After wet weather, the sea close around the shores of the British Islands is sometimes made turbid by the quantity of mud washed by rain and streams from the land. Dr. Carpenter found the bottom-waters of the Mediterranean to be everywhere permeated by an extremely fine mud, derived no doubt from the rivers and shores of that sea. He remarks that the characteristic blueness of the Mediterranean, like that of the Lake of Geneva, may be due to the diffusion of exceedingly minute sedimentary particles through the water.

The great oceanic currents are probably powerful agents in the transport of fine detritus and of living and dead organisms. Coral-reefs appear to flourish best where these currents bring a continuous and abundant supply of food to the reef-builders. The reefs, in turns, furnish an enormous quantity of fine silt, produced by the pounding action of breakers upon them. Before the silt can sink to the bottom, it may be transported to vast distances. The lower portion of the Gulf Stream, from its exit in the Florida Channel northward to Cape Hatteras, a distance of 700 miles, has been compared to a huge muddy river, carrying its silt to the steep slope south of that cape, and depositing here and there patches of green sand along the sides of its course, while the upper waters remain perfectly clear and of the deepest blue. The silt is partly derived from the abrasion of coral-reefs, partly from the decay of the abundant pelagic fauna swept onward by the current. Professor A. Agassiz has called attention to the important part which the great oceanic currents, in ancient as in modern times, may have played in the accumulation of limestones, not only by transporting calcareous organisms, but by bringing an abundant food-supply and thereby nourishing a prolific fauna along their track.[2]

During the voyage of the *Challenger*, from the abysses of the Pacific Ocean, at remote distances from land, the dredge brought up bushels of rounded pieces of pumice of all sizes up to blocks a foot in diameter. These fragments were all evidently waterworn, as if derived from land, though we are still ignorant of the extent to which they may have been supplied by submarine volcanic eruptions. Some small pieces were taken on the surface of the ocean in the tow-net. Round volcanic islands, and off the coasts of volcanic tracts of the mainland, the sea is sometimes covered with floating pieces of water-worn pumice swept out by flooded rivers. These fragments may drift away for hundreds or even thousands of miles until, becoming water-logged, they sink to the bottom. The

[1] See charts of part of North Atlantic by Messrs. Siemens Brothers & Co., London, 1882. Some specimens shown to me by Messrs. Siemens are pieces of basalt which may have come from Greenland.

[2] *Amer. Acad.* xi. (1882), p. 126.

universal distribution of pumice was one of the most noticeable features in the dredgings of the *Challenger*. The clay which is found on the bottom of the ocean, at the greatest distances from any shore, contains only volcanic minerals, and appears to be due to the trituration of volcanic detritus. In approaching the continents, at a distance of several hundred miles from shore, traces of the minerals of the crystalline rocks of the land begin to make their appearance.[1]

Another not unimportant process of marine transport is that performed by floating ice. In the arctic regions, as we have seen, vast quantities of detritus become bedded with the ice at the bottom of the glaciers as these approach the sea. The icebergs that float off from these glaciers, though their visible parts may be pure clean ice, are thus freighted with rubbish below, which when a berg capsizes is not infrequently brought up to the surface as a black mass. Owing, however, to the more rapid melting of the portion of the ice that is immersed in the sea, most of the detritus is probably thrown down on the bottom not very far from land. Occasional instances, however, have been observed, hundreds of miles to the south, where blocks of rock or portions of earth still remained on the bergs. It is estimated that thousands of tons of boulders, gravel, and clay are every year sent into the sea from the front of each large glacier in North Greenland, and that much of this freight is borne out of the fjords into Baffin's Bay.[2] The floor of certain portions of the North Atlantic in the pathway of the annual fleet of icebergs may thus be plentifully strewn with ice-borne detritus. By means also of the sea-ice that freezes to the shores, an enormous quantity of earth and stones is every year borne away on the disrupted floes, and is strewn over the floor of the sounds, bays and channels. Professor Tarr, in voyaging along the American coast for a thousand miles north of the Straits of Belle Isle and almost continuously amongst floe-ice, estimated that about one per cent of the cakes carried débris of some kind, while in some cases they were quite black with it, and fully half of them were discoloured with the sediment they were carrying.[3]

Exceptional methods of transport have been noted in various parts of the oceans. Thus in south-western Patagonia, Nordenskjöld found bits of slate which, though specifically heavier than the water, were kept afloat for some time on the surface of the sea.[4] Occasionally fine dry sand, blown by the wind to a surface of smooth water, may be observed to float there for a time.[5] A more singular mode of conveyance by which pebbles may be carried for great distances is where they have been swallowed by fishes.[6]

(4) Reproduction.—The sea, being the receptacle for the material worn away from the land, must receive and store up in its depths all that

[1] Murray, *Proc. Roy. Soc. Edin.* 1876-77, p. 247. Considerable quantities of pumice and slag are from time to time drifted to the coasts of Northern Europe (Bäckström, *Bihang. Svensk. Vet. Akad. Handl.* xvi. ii. No. 5, 1890). There can be little doubt, however, that much of this material has come from the cleaning out of the furnaces of sea-going steamers.

[2] R. S. Tarr, *Amer. Jour. Sci.* iii. (1897), p. 228. [3] *Op. cit.* p. 227.

[4] *Geol. Fören. Stockholm*, xxi. p. 587.

[5] F. W. Simonds, *Amer. Geol.* xvii. (1896), p. 29.

[6] L. Vaillant, *B. S. G. F.* 3rd ser. xix. (1892), p. 111.

vast amount of detritus by the removal of which the level and contours of the land are in the course of time so greatly changed. The deposits which take place within the area covered by the sea may be divided into two groups—the inorganic and organic. It is the former with which we have at present to deal; the latter will be discussed with the other geological functions of plants and animals (pp. 605, 610, 613 *seq.*). The inorganic deposits of the sea-floor are (i.) chemical and (ii.) mechanical.

(i.) Of Chemical deposits now forming on the sea-floor we know as yet very little, save as regards those that take place in shallow enclosed basins where they come directly under observation. On the Morbihan coast in the north-west of France, for example, the enclosure of extensive shallow lagoons of sea-water has been completed artificially, and from these basins 100,000 to 200,000 tons of salt are annually obtained. The salt is not pure chloride of sodium, but contains some chlorides of magnesium and calcium with traces of bromides and iodides. Other substances of great geological interest are deposited from chemical solution, more particularly gypsum, crystals of which 3 to 4 centimetres in size are formed on the bottoms of some of these lagoons. The formation of these crystals, however, is probably due in main part if not entirely to the co-operation of certain bacteria, which liberate sulphur by oxidising sulphuretted hydrogen, and then by a second process of oxidation transform the sulphur into sulphuric acid, which chiefly combines with lime.[1]

At the mouth of the Rhône a crystalline calcareous deposit accumulates, in which the débris of the sea-floor is enveloped. Bischof estimated that no precipitation of carbonate of lime could take place from sea-water until after $\frac{17}{18}$ of the water had evaporated.[2] No deposit of lime in the open sea is possible from concentration of sea-water. But the calcareous formation on the sea-bottom opposite rivers like the Rhône, if not the result of the precipitation of lime by plants or animals, may perhaps be explained by supposing that as the layer of river-water floats and thins out over the surface of the sea in warm weather with rapid evaporation, its comparatively large proportion of carbonate of lime may be partially precipitated. It has been observed near Nice, as well as on the African coasts and other parts of the Mediterranean shores, that on shore-rocks within reach of the water a hard varnish-like crust is deposited. This substance consists essentially of carbonate of lime. As it extends over rocks of the most various composition, it has been regarded as a deposit of lime held in solution in the shore sea-water, and rapidly evaporated in pools or while bathing the surface of rocks exposed to strong sun-heat.[3] But it may possibly be due to organic agency like the amorphous crust of limestone formed by nullipores (see *postea*, p. 605).

During the researches of the *Challenger* expedition, important facts in

[1] C. Barrois, *Ann. Soc. Géol. Nord.* xxiv. (1896), p. 198; Winogradsky, *Botanische Zeitung*, 1887.

[2] 'Chem. Geol.' i. p. 178.

[3] *Bull. Soc. Géol. France* (3), ii. p. 219; iii. p. 46; vi. p. 84. See *postea*, p. 624, where the evaporation in the coral-seas is referred to.

the history of marine chemistry were obtained from the abysses of the Atlantic and Pacific oceans. The precipitation of hydrates of manganese and iron was found to take place there on an extensive scale, and this process has since been observed in many other seas even in water of no great depth. Some of the mineral precipitations on the sea-bottom have an evident relation to the influence of organisms or organic matter, as is more especially indicated by the glauconitic and phosphatic deposits which are there laid down, and to which fuller reference is made in the account of the action of plant and animal life (pp. 626, 627). It may be added here that even crystals of a zeolite have been ascertained to be in course of formation among the clays of the deep sea, as will be more particularly noted on p. 585.

(ii.) The Mechanical deposits of the sea may be grouped into subdivisions according as they are directly connected with the waste of the land, or have originated at great depths and remote from land, when their source is not so obvious.[1]

A. *Land-derived or Terrigenous.*—These may be conveniently grouped according to their relative places on the sea-bed.

*a.* Shore Deposits.—The most conspicuous and familiar are the layers of gravel and sand which accumulate between tide-marks. As a rule, the coarse materials are thrown up about the upper limit of the beach. They seem to remain stationary there; but if watched and examined from time to time, they will be found to be continually shifted by high tides and storms, so that, though the bank or bar of shingle retains its place, its component pebbles are being constantly moved. During gales coincident with high tides, coarse gravel may be piled up considerably above the ordinary limit of the waves in the form of what are termed *storm-beaches.*[2] Below the limit of coarse shingle upon the beach lies the zone of fine gravel, and then that of sand, the sediment, though liable to irregular distribution, yet tending to arrange itself according to coarseness and specific gravity, the rougher and heavier detritus lying at the upper, and the finer and lighter towards the lower edge of the shore. The nature of the littoral accumulations on any given part of a coast-line must depend either upon the character of the shore-rocks which at that locality are broken up by the waves, or upon the set of the shore-currents, and the kind of detritus they bear with them. Coasts exposed to heavy surf, especially where of a rocky character, are apt to present beaches of coarse shingle between their projecting promontories. Sheltered

[1] See on this subject an important memoir by Messrs. Murray and Renard, *Proc. Roy. Soc. Edin.* 1884, and *Nature,* xxx. (1884); also Murray, *Proc. Roy. Soc.* 1876; *Proc. Roy. Soc. Edin.* ix.; Murray and Renard, *Brit. Assoc.* 1879, Sects. p. 340; also for the North Atlantic, 'Den Norske Nordhavs-Expedition,' part ix. (on Oceanic Deposits), 1882. A. Agassiz, 'Three Cruises of the *Blake,*' i. p. 260. J. Y. Buchanan, *Proc. Roy. Soc. Edin.* xviii. (1891), p. 131. Murray and Irvine, *Trans. Roy. Soc. Edin.* xxxvii. (1893), p. 481. J. B. Harrison and A. J. Jukes Browne, *Q. J. G. S.* li. (1895), p. 313. But the chief source of information is the great memoir on "Deep-Sea Deposits" by Messrs. Murray and Renard, in the *Reports of the Challenger Expedition,* 1891, already cited.

[2] G. H. Kinahan on sea-beaches, *Proc. Roy. Irish Acad.* 2nd ser. iii. p. 101.

bays, on the other hand, where wave-action is comparatively feeble, afford a gathering-ground for finer sediment, such as sand and mud. Estuaries and inlets, into which rivers enter, frequently show wide muddy flats at low water (p. 510). Deposits of comminuted shells, coral-sand, or calcareous organic remains thrown up on shore, may be cemented into compact rock by the solution and redeposit of carbonate of lime (p. 624). Where tidal currents sweep along a coast yielding much detritus, long bars or shoals may form parallel with the shore. On these the shingle and sand are driven coastwise in the direction of the prevalent current.[1] They not infrequently accumulate as long barriers completely protecting the shores from which they are separated by a channel or lagoon of fresh or brackish water (p. 511). Into this lagoon sediment is washed from the land and aquatic vegetation takes root there, until not infrequently a salt-marsh or swamp is formed. Extensive accumulations of this kind are to be found along the eastern coast of the United States.[2]

Among the deposits cast ashore by the sea, not the least interesting are the masses of driftwood which, carried down by rivers, are borne by marine currents, sometimes for hundreds of miles, and thrown down in huge accumulations in protected bays. It is in the arctic seas that this phenomenon obtains its greatest development. Prodigious quantities of terrestrial vegetation are swept by the Siberian rivers into these waters and are carried westwards until stranded in sheltered bays of the coast and of the islands. Every shoal coast of Spitzbergen presents examples of these heaps of driftwood.[3]

*β*. Infra-Littoral and Deeper-Water Deposits.—These extend from below low-water mark to a depth of sometimes as much as 2000 fathoms, and reach a distance from land varying up to 200 miles or even more. Near land, and in comparatively shallow water, they consist of banks or sheets of sand, more rarely mixed with gravel. The bottom of the North Sea, for example, which between Britain and the continent of Europe lies at a depth never reaching 100 fathoms, is irregularly marked by long ridges of sand, enclosing here and there hollows where mud has been deposited. In the English Channel, large banks of gravel extend through the Straits of Dover as far as the entrance to the North Sea.[4] These features seem to indicate the line of the chief mud-bearing streams from the land, and the general disposition of currents and eddies in the

[1] See the authorities cited on p. 576, regarding the Chesil Bank, and F. Merrill, "Barrier-beaches of the Atlantic Coast," *Pop. Sci. Monthly*, October 1890; M. Jefferson, "Beach Cusps," *Journ. Geol.* 1900, p. 237; J. C. Branner, *op. cit.* p. 481.

[2] N. S. Shaler on sea-coast swamps, *6th Ann. Rep. U. S. Geol. Surv.* 1884-85, p. 353.

[3] Nordenskjöld's '*Vega* Expedition.' *Petermann's Geograph. Mittheil.* Ergänzungsheft No. 16, where a map of these accumulations on the arctic coasts is given.

[4] For information as to the English Channel and other parts of the British seas, see J. T. Harrison, *Min. Proc. Inst. Civ. Engin.* vii. (1848), p. 327 (where a map of the submarine deposits will be found); R. A. C. Godwin-Austen, *Quart. Journ. Geol. Soc.* vi. (1849), p. 69—a paper of singular interest and importance; Lebour, *Proc. Geol. Assoc.* iv. p. 158; John Murray, *Min. Proc. Inst. Civ. Engin.* xx. (1860-61), where a map of the North Sea floor is given which is of great interest as indicating some of the ancient terrestrial features of that submerged land-surface; W. H. Wheeler, 'The Sea-coast,' 1902.

sea which covers that region, the gravel ridges marking the tracts or junctions of the more rapidly moving currents, while the muddy hollows point to the eddies where the fine sediment is permitted to settle on the bottom. The more prominent features on the floor of the North Sea, however, are probably of much older date than the deposits now accumulating there. Some of them are doubtless relics of the time when the floor of that sea was a broad terrestrial plain. The Dogger Bank, for instance, is probably a prolongation of the Jurassic escarpment of the Yorkshire coast. Other minor submarine features may be partly due to irregular deposition of glacial drift.

During the course of the voyage of the *Challenger*, the approach to land could always be foretold from the character of the bottom, even at distances of 150 and 200 miles. The deposits were found to consist of blue and green muds derived from the degradation of older crystalline rocks. The blue or dark slate-coloured mud takes its colour from decomposing organic matter and sulphide of iron, frequently giving off the odour of sulphuretted hydrogen, and assuming a brown or red hue at the surface, owing to oxidation. Besides occurring in deposits of deep water, iron-disulphide is met with in many shallow seas, and on some coasts it cements sand, gravel and shells into a coherent mass.[1] The chemical changes that result in the elimination of sulphides from sea-water may be explained by supposing that the decomposing animal and vegetable matter of the sea-floor reduces the sulphates to sulphides, which in turn react on the iron and manganese minerals (principally silicates) in the mud, forming sulphides of those metals. Subsequently the oxygen of the water converts the sulphides to oxides, which gather into concretionary forms.[2] The green muds found at depths of 100 to 700 fathoms are characterised by the presence of a considerable quantity of glauconite grains, either isolated or united into concretions, and frequently filling the chambers of *Foraminifera* or other organisms. Round volcanic islands, the bottom is covered with grey volcanic mud and sand derived from the degradation of volcanic rocks. These deposits can be traced to great distances; from Hawaii they extend for 200 miles or more. Pieces of pumice, scoriæ, &c., occur in them, mingled with marine organisms, and more particularly

[1] H. Reusch, *Neues Jahrb.* 1879, p. 255.

[2] J. Y. Buchanan, *Brit. Assoc.* 1881, p. 584. Mr. Buchanan, in renewing this investigation and obtaining many illustrations from the seas around Scotland, has shown that the mud on many parts of the sea-bottom is being continually passed and repassed through the bodies of animals which live upon it. The mineral matter is thus brought in contact with the organic secretions of the animals and is ground up with these in their milling organs. The reducing action of the secretions produces, Mr. Buchanan believes, sulphides from the sulphates of sea-water, and these sulphides, acting on the ochreous matter of the bottom, give rise to sulphides of iron and manganese, which, being very unstable in presence of water and oxygen, are, where they lie on the surface, soon transformed into oxides. *Proc. Roy. Soc. Edin.* xviii. (1890), p. 17, "On the Occurrence of Sulphur in Marine Muds." The blue mud on exposure rapidly turns yellow from oxidation, but the upper oxidised layer appears to protect the mud below, which retains its colour and composition. Another view of the decomposition of the sulphates of sea-water is proposed by Sir John Murray and Mr. Irvine. See *postea*, p. 618, and paper there quoted.

with abundant grains, incrustations and nodules of an earthy peroxide of manganese (Fig. 179). Near coral-reefs the sea-floor is covered with a white calcareous mud derived from the abrasion of coral, and frequently containing 95 per cent of carbonate of lime. Beyond a depth of 1000 fathoms, coral mud gives place to a Globigerina ooze or red clay. The east coast of South America supplies a peculiar red mud which is spread over the Atlantic slope down to depths of more than 2000 fathoms.

Throughout these land-derived sediments are found minute particles of recognisable minerals. Of these, quartz, often in rounded grains, plays the chief part. Next comes mica, felspar, augite, hornblende and other less abundant constituents of terrestrial rocks, the materials becoming coarser towards land. Occasional pieces of wood, portions of fruits, and leaves of trees in the same deposits further indicate the reality of the transport of material from the land. Shells of pteropods, larval gasteropods, and lamellibranchs are tolerably abundant in these muds, with many infra-littoral species of *Foraminifera*, and diatoms. Below 1500 or 1700 fathoms, pteropod shells seldom appear, while at 3000 fathoms hardly a foraminifer or any calcareous organism remains.[1]

In some regions vast quantities of terrestrial vegetation are strewn over the sea-bottom, even at depths of 2000 fathoms, and at distances of several hundred miles from land. This fact has been observed by Professor Agassiz off Central America, both in the Atlantic and Pacific Oceans, hardly a single haul of the dredge failing to bring up much vegetable matter, and frequently logs, branches, twigs, seeds, leaves and fruits.[2]

B. *Abysmal or Pelagic.*[3]—Passing over at present the organic deposits which form so characteristic a feature on the floor of the deeper and more open parts of the ocean, we come to certain red and grey clays found at depths of more than 2000 fathoms, down to the bottoms of the deepest abysses. These, by far the most widespread of oceanic deposits,[4] consist of exceedingly fine clay, coloured sometimes red by iron-oxide, sometimes of a chocolate tint from manganese oxide, with grains of augite, felspar, and other volcanic minerals, pieces of palagonite and pumice, nodules of peroxide of manganese, and other mineral substances, together with *Foraminifera*, and in some regions a large proportion of siliceous *Radiolaria*. These clays result from the decomposition of pumice and fine volcanic dust, transported from volcanic islands into mid-ocean, or from the accumulation of the detritus of submarine eruptions. The extreme slowness of deposit is strikingly brought out in the tracts of sea-floor farthest removed from land. From these localities great numbers of

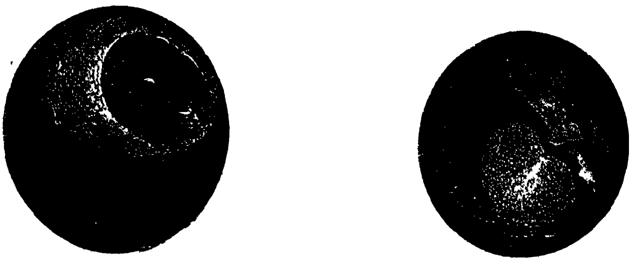
[1] See papers by Messrs. Murray and Renard, quoted on p. 580, and vol. of *Challenger Report* on "Deep-Sea Deposits," p. 190.

[2] 'Three Cruises of the *Blake*,' and *Bull. Mus. Comp. Zool.* xxiii. No. 1 (1892), p. 11.

[3] For information regarding the fauna and deposits of the ocean-abysses, the works quoted on p. 580 may be consulted; also various writings of Professor A. Agassiz, besides his 'Three Cruises of the *Blake*,' especially papers in *Bull. Mus. Comp. Zool.* xxi. No. 4, and xxxiii. No. 1; and Haeckel's 'Plankton-Studien,' 1890.

[4] They are estimated to cover upwards of 50,000,000 square miles of the sea-floor. Murray and Irvine, *Proc. Roy. Soc. Edin.* xvii. (1889), p. 82.

sharks' teeth, with ear-bones and other bones of whales, were dredged up in the *Challenger* Expedition,—some of them quite fresh, others



a b

Fig. 177.—Magnetic Spherules (Cosmic Dust) of the ocean-bottom. (Murray and Renard.)

*a*, Black spherule with metallic centre (magnified 60 diameters) from a depth of 2375 fathoms in South Pacific. This represents the common form of these particles, and shows the usual depression on one part of the surface. There is a lustrous crust of magnetite outside.

*b*, Similar spherule (60 diam.) from which the crust of magnetic oxide has been broken off to show the inner metallic nucleus, here represented by the central lighter part. 3150 fathoms in the Atlantic.

partially crusted with peroxide of manganese, and some wholly and thickly surrounded with that substance. We cannot suppose that sharks and whales so abounded in the sea at one time as to cover the floor of the ocean with a continuous stratum of their remains. No doubt each haul of the dredge, which brought up so many bones, represented the droppings of many generations. The successive stages of manganese incrustation point to a long, slow, undisturbed period, when so little sediment accumulated that the bones dropped at the beginning remained at the end still uncovered, or only so slightly covered as to be easily scraped up by the dredge. In these deposits, moreover, occur numerous minute spherular particles of metallic iron and "chondres," or spherical internally radiated particles referred to bronzite, which are in all probability of cosmic origin—portions of the dust of meteorites which in the course of ages have fallen upon the sea-bottom (Figs. 177, 178). Such particles, no doubt, fall all over the ocean; but it is only on those parts of the bottom which, by reason of their distance from any land, receive accessions of deposit with extreme slowness—and where therefore the present surface may contain the dust of a long succession of years—that it may be expected to be possible to detect them.[1]

Fig. 178.—Chondre (Cosmic Dust) of the ocean-bottom. (Murray and Renard.)

Spherule of bronzite (mag. 25 diam.) showing the aspect of the chondres found in the abysmal deposits. From a depth of 3500 fathoms, Pacific.

[1] Murray and Renard on cosmic dust, *Proc. Roy. Soc. Edin.* 1884; *Nature*, xxix.; *Challenger Expedition Report*, vol. on "Deep-Sea Deposits," p. 327 *et seq.*

The abundant deposit of peroxide of manganese over the floor of the deep sea is one of the most singular features of recent discovery. It occurs as an earthy incrustation round bits of pumice, bones and other objects (Fig. 179). The nodules possess a concentric arrangement of lines not unlike those of urinary calculi. That they are formed on the spot, and not drifted from a distance, was made abundantly clear from their containing abysmal organisms, and enclosing more or less of the surrounding bottom, whatever its nature might happen to be. More recently Mr. J. Y. Buchanan dredged similar small manganese concretions from some of the deeper parts of Loch Fyne,[1] and subsequently Sir John

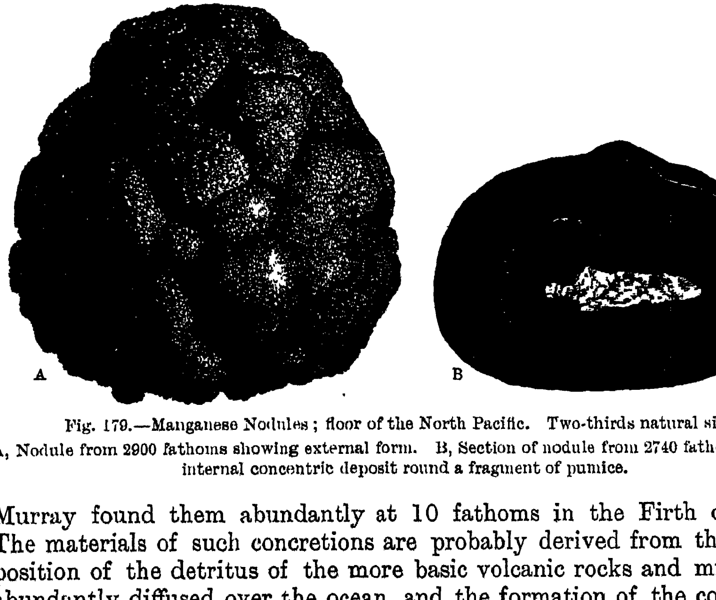



Fig. 179.—Manganese Nodules; floor of the North Pacific. Two-thirds natural size.[2]
A, Nodule from 2900 fathoms showing external form. B, Section of nodule from 2740 fathoms showing internal concentric deposit round a fragment of pumice.

Murray found them abundantly at 10 fathoms in the Firth of Clyde. The materials of such concretions are probably derived from the decomposition of the detritus of the more basic volcanic rocks and minerals so abundantly diffused over the ocean, and the formation of the concretions may be analogous to the solution and deposition of oxides of iron and manganese by organic acids, as on lake-floors, bogs, &c. (p. 612).[3] In connection with the chemical reactions indicated by these nodules as taking place on the sea-bottom, further reference may be made here to the still more remarkable discovery of Messrs. Murray and Renard in the course of their examinations of the materials brought up from the same abysmal deposits. Minute crystals, simple, twinned, or in

[1] *Nature*, xviii. (1878), p. 628. *Brit. Assoc.* 1881, p. 583. *Proc. Roy. Soc. Edin.* ix. p. 287. *Trans. R. S. Edin.* xxxvi. (1891), p. 459. Dieulafait, *Comptes rend.* 1884, p. 589.

[2] These and Fig. 178 are taken from Plate xxxiii. of the vol. on "Deep-Sea Deposits" in the *Reports of the Challenger Expedition*. The detailed investigation by Messrs. Murray and Renard of the deep-sea deposits obtained by this expedition forms the most important contribution yet made to our knowledge of the oceanic abysses.

[3] Different views have been expressed by Sir John Murray and Mr. J. Y. Buchanan as to the mode of origin of the marine manganese deposits. See R. Irvine and J. Gibson, *Proc. Roy. Soc. Edin.* xviii. (1891), p. 54.

spheroidal groups, which occur abundantly in the typical red clay of the central Pacific, have been identified with the zeolite known as phillipsite. These crystals have certainly been formed directly on the sea-bottom, for they are found gathered round abysmal organisms, and their production has been effected at about the temperature of 32° Fahr. They occur in regions where detritus of basalt and palagonite is abundant, and they have probably been formed by a series of transformations similar to those by which zeolites have been produced so abundantly among basaltic rocks on land. Some examples of red clays dredged up between the Society and Sandwich Islands were found to contain between 20 and 30 per cent of the mineral.[1] The importance of these facts in reference to the chemistry of marine deposits is at once obvious.

From a comparison of the results of the dredgings made in recent years in all parts of the oceans, it is impossible to resist the conclusion that there is little in the character of the deep-sea deposits which finds a parallel among the marine geological formations visible to us on land. It is only among the comparatively shallow-water accumulations of the existing sea that we encounter obvious analogies to the older formations. And thus we reach, by another and a new approach, the conclusion which on other and very different grounds has been arrived at, viz., that the present continental axes have existed from the remotest times, and that the marine strata which constitute so large a portion of their present mass have been accumulated not as deep-water deposits, but in comparatively shallow water along their flanks or over their submerged ridges.[2]

## § 7. Denudation and Deposition.—The results of the action of Air and Water upon Land.[3]

It may be of advantage, before passing from the subject of the geological work of water, to consider the broad results achieved by the co-operation of all the inorganic forces by which the surface of the land is worn down. These results naturally group themselves under the two heads of Denudation and Deposition.

### 1. *Subaerial Denudation—the general lowering of land.*

The true measure of denudation is to be sought in the amount of mineral matter removed from the surface of the land and carried into the sea. This is an appreciable and measurable quantity. There may be room for discussion as to the way in which the waste is to be

[1] "Deep-Sea Deposits," pp. 400-410.

[2] *Proc. Roy. Geograph. Soc.* July 1879.

[3] This section is mainly taken from an essay by the author, *Trans. Geol. Soc. Glasgow,* iii. p. 153. The subject has been discussed anew on the basis of more exact knowledge of the interior of the continents and the depths of the sea by Sir John Murray, *Scottish Geograph. Mag.* 1887. See also a note by Dr. C. Davison, *Geol. Mag.* 1889, p. 409. A. De Lapparent, *Bull. Soc. Géol. France,* xviii. (1890), p. 351.

apportioned to the different forces that have produced it, but the total amount of sea-borne detritus must be accepted as a fact about which, when properly verified, no further question can possibly arise. In this manner the subject is at once disencumbered of difficulty in fixing the relative importance of rain, rivers, frost, glaciers, &c., considered as denuding agents. We have simply to deal with the sum-total of results achieved by all these forces acting severally and conjointly. Thus considered, this subject casts a new light on the origin of existing land-surfaces, and affords some fresh data for approximating to a measure of past geological time.

Of the mineral substances received by the sea from the land, by much the larger portion is brought down by streams; a relatively small amount is washed off by the waves of the sea itself. It is the former, or stream-borne part, which is at present to be considered. The quantity of mineral matter carried every year into the ocean by the rivers of a continent represents the amount by which the general surface of that continent is annually lowered. Much has been written of the vastness of the yearly tribute of silt borne to the ocean by such streams as the Gànges and Mississippi; but "the mere consideration of the number of cubic feet of detritus annually removed from any tract of land by its rivers does not produce so striking an impression upon the mind as the statement of how much the mean surface-level of the district in question would be reduced by such a removal."[1] This method of inquiry is so obvious and instructive that it probably received attention from early geologists, though data were still wanting for its proper application. Playfair, for instance, in speaking of the transference of material from the surface of the land to the bottom of the sea, remarks that "the time requisite for taking away by waste and erosion 2 feet from the surface of all our continents and depositing it at the bottom of the sea cannot be reckoned less than two hundred years."[2] This estimate does not appear to have been based on any actual measurements, and must greatly exceed the truth; but it serves to indicate how broad was the view that Playfair held of the theory which he undertook to illustrate. The first geologist who appears to have attempted to form any estimate on this subject from actually ascertained data, was Mr. Alfred Tylor, who in the year 1850 published a paper in which he estimated the probable amount of solid matter annually brought into the ocean by rivers and other agents. He inferred that the quantity of detritus now distributed over the sea-bottom every year would, at the end of 10,000 years, cause an elevation of the ocean-level to the extent of at least 3 inches.[3] The subject was afterwards taken up by Croll,

[1] Tylor, *Phil. Mag.* 4th series, v. (1850), p. 268.

[2] 'Illustrations,' p. 424. Manfredi had previously made a calculation of the amount of rain that falls over the globe, and of the quantity of earthy matter carried into the sea by rivers. He estimated that this earthy matter distributed over the sea-bed must raise the level of the latter five inches in 348 years. Von Hoff, 'Veränderungen der Erdoberfläche,' Band i. p. 232. See the other authorities there cited.

[3] *Phil. Mag. loc. cit.*

;ho specially drew attention to the Mississippi as a measure of denuda- ion and thereby of geological time.[1]

When the annual discharge of mineral matter carried seaward by a iver, and the area of country drained by that river, are both known, the ne sum divided by the other gives the amount by which the drainage- rea has its mean general level reduced in one year. For it is clear that f a river carries so many millions of cubic feet of sediment every year nto the sea, the area drained by it must have lost that quantity of solid naterial; and if we could restore the sediment so as to spread it over the asin, the layer so laid down would represent the fraction of a foot by vhich the surface of the basin had been lowered during a year.

It has been already shown that the material removed from the land y streams is twofold—one portion is chemically dissolved, the other is nechanically suspended in the water or pushed along the bottom. 'roperly to estimate the loss sustained by the surface of a drainage- asin, we ought to know the amount of mineral matter removed in each f these conditions, and also the volume of water discharged, from neasurements and estimates made at different seasons and extending ver a succession of years. These data have not yet been fully collected rom any river, though some of them have been ascertained with pproximate accuracy, as in the Mississippi Survey of Messrs. Hum- hreys and Abbot, and the Danube Survey of the International Com- nission. As a rule, more attention has been shown to the amount of nechanically suspended matter than to that of the other ingredients. t will be borne in mind, therefore, that the following estimates, in so ar as they are based upon only one portion of the waste of the land —that carried in mechanical suspension,—are understatements of the ruth.[2]

The proportion of mineral substances held in suspension in the water of ivers has been already (pp. 490-496) discussed. It is most advantageous o determine the amount of mineral matter by weight, and then from its verage specific gravity to estimate its bulk as an ingredient in river- vater. The proportion by weight is probably, on an average, about half hat by bulk.

It may seem superfluous to insist that the earthy matter borne into he sea from any given area represents so much actual loss from the urface of that area. Yet this self-evident statement is probably not ealised by many geologists to the extent which it deserves. If a tream removes in one year one million of cubic yards of earth from its

[1] *Phil. Mag.* for February 1867 and May 1868; and his 'Climate and Time.' See also 'eol. Mag. June 1868; *Trans. Geol. Soc. Glasgow*, iii. p. 153.

[2] Geologists are largely indebted to Mr. Mellard Reade for the attention which he has ven to the important part played by chemical solution in the general denudation of the nd. From the data collected by him he infers, as the proportion of solids in solution in ie water of the Mississippi is $\frac{1}{5019}$ by weight, about 150 millions of tons of dissolved ineral must be carried by this river annually into the sea. In the River Plate the propor- on is $\frac{1}{6458}$, in the St. Lawrence $\frac{1}{8616}$, in the Amazon $\frac{1}{18620}$. Presidential Address. iverpool Geol. Soc. 1884.

drainage-basin, that basin must have lost one million of cubic yards from its surface. From the data and authorities which have already been adduced (p. 494), the subjoined table has been constructed, in which are given the results of the measurement of the proportion of sediment in a few rivers. The last column shows the fraction of a foot of rock (reckoning the specific gravity of the silt at 1·9 and that of rock at 2·5) which each river must remove from the general surface of its drainage-basin in one year.

| Name of River. | Area of basin in square miles. | Annual discharge of sediment in cubic feet. | Fraction of foot of rock by which the area of drainage is lowered in one year. |
| --- | --- | --- | --- |
| Mississippi . . | 1,147,000 | 7,468,694,400 | $\frac{1}{6000}$ |
| Ganges (Upper) . | 143,000 | 6,368,077,440 | $\frac{1}{823}$ |
| Hoang Ho . . | 700,000 | 17,520,000,000(?) | $\frac{1}{1464}$ |
| Rhône . . | 25,000 | 600,381,800 | $\frac{1}{1528}$ |
| Danube . . | 234,000 | 1,253,738,600 | $\frac{1}{6846}$ |
| Po . . . | 30,000 | 1,510,137,000 | $\frac{1}{729}$ |

At the present rate of erosion, the rivers named in this table remove one foot of rock from the general surface of their basins in the following ratio:—The Mississippi removes one foot in 6000 years; the Ganges above Ghazipûr does the same in 823 years;[1] the Hoang Ho in 1464 years; the Rhône in 1528 years; the Danube in 6846 years; the Po in 729 years. If these rates should continue, the Mississippi basin will be lowered 10 feet in 60,000 years, 100 feet in 600,000 years, 1000 feet in 6,000,000. Assuming Humboldt's estimate of the mean height of the North American continent, 748 feet,[2] we find that at the Mississippi's rate of denudation, this continent would be worn away in about four and a half million years. The Ganges works still more rapidly. It removes one foot of rock in 823 years, and if Humboldt's estimate of the average height of the Asiatic continent be accepted, viz., 1132 English feet, that mass of land, worn down at the rate at which the Ganges destroys it, would be reduced to the sea-level in little more than 930,000 years. Still more remarkable is the extent to which the river Po denudes its area of drainage. Even though measurements had not been made of the ratio of sediment contained in its water, we should be prepared to find that proportion a remarkably large one, if we look at the enormous changes which, within historic times, have been made

[1] In my original paper the area of drainage of the Ganges was given as 432,480 square miles. But the area from which the annual discharge of silt was there given was only that part of the Gangetic basin above Ghazipûr, which Dr. Haughton estimated at 143,000 square miles (*Proc. Roy. Dublin Soc.* 1879, No. xxxix.). Hence, as he pointed out, the rate of erosion is really much greater than I had made it. I have recalculated the rate from the altered data, and the result is as given above.

[2] *Ante*, pp. 48, 49, where other and more reliable estimates of the mean heights of the continents are given. But as the numbers do not affect the argument, those originally assumed are here retained.

by the alluvial accumulations of this river (pp. 506, 516). If the Po removes one foot of rock from its drainage basin in 729 years, it will lower that basin 10 feet in 7290 years, 100 feet in 72,900 years. If the whole of Europe (taken at a mean height of 671 feet) were denuded at the same rate, it would be levelled in rather less than half a million of years.

It is not pretended that these results are strictly accurate. On the other hand, they are not mere guesses. The amount of water flowing into the sea, and the annual discharge of sediment, have been in each case measured with greater or less precision. The areas of drainage may perhaps require to be increased or lessened. But though some change may be made upon the ultimate results just given, it is hardly possible to consider them attentively without being forced to ask whether those enormous periods which geologists have been in the habit of demanding for the accomplishment of geological phenomena, and more especially for the very phenomena of denudation, are not in reality far too vast. If the Mississippi is carrying on the process of denudation so rapidly that at the same rate the whole of North America might be levelled in four and a half millions of years, surely it is most unphilosophical to demand unlimited ages for similar but often much less extensive denudations in the geological past. Moreover, that rate of erosion appears, on the whole, to be rather below the average in point of rapidity. The Po, for instance, works more than eight times as fast. But as the physics of the Mississippi have been more carefully studied than those of perhaps any other river, and as that river drains so extensive a region, embracing so many varieties of climate, rock, and soil, we shall probably not exaggerate the result if we assume the Mississippi ratio as an average.[1] It is, of course, obvious that as the level of the land is lowered, the rate of subaerial denudation decreases, so that, on the supposition that no subterranean movements took place to aid or retard the denudation, the last stages in the demolition of a continent must be enormously slower than during earlier periods.

It must not be forgotten, however, that, as already remarked, the estimates here given, inasmuch as they are based only on the material removed in mechanical suspension, are probably understatements of the truth. If we take into account also the material carried away in chemical solution, the rate of subaerial denudation will be considerably heightened. It is difficult, however, to apportion the loss of dissolved substance from the surface of the land. The salts contained in solution in river-water are derived not only from the superficial rocks, but probably to a much greater extent from springs which sometimes carry up dissolved substances from considerable depths. In the end, no doubt, as the level of the land is reduced by subaerial waste, this subterranean solution will tell, but it can hardly be said sensibly to affect the lowering of the level from century to century. Mr. Mellard Reade, from his researches into this subject, believes that the amount of solids in solution is on the whole about

[1] Dr. Davison (in the paper cited on p. 586) states that the annual rate of denudation might be taken from the average of the river-basins in the table above, including those of the Rhône and the Nith, giving a mean of one foot in every 2409 years.

one-third of that of those in suspension. He finds this to be the ratio in the Nile, the Danube and the Mississippi, the last-named being in many respects a typical river. If, as he proposes, we add this additional loss by chemical solution to the amount of material removed in mechanical suspension from the Mississippi basin, the annual lowering of the level of the basin will be raised from $\frac{1}{6000}$ to $\frac{1}{4500}$ of a foot.[1] It is quite true that the loss of mineral matter from the whole basin would be equivalent to that sum, but there would obviously not be strictly a lowering of the level of the basin to that amount. It is difficult to see how we are to discriminate between superficial and subterranean solution; and until some separation of this kind is made, it seems hardly legitimate to class the whole of the dissolved matter with that carried in mechanical suspension as a measure of the annual loss from the surface of the land.

There is another point of view from which a geologist may advantageously contemplate the active denudation of a country. He may estimate the annual rainfall and the proportion of water which returns to the sea. If he can obtain a probable average ratio for the earthy substances contained in the river-water which enters the sea, he will be able to estimate the mean amount of loss sustained by the whole country. Thus, taking the average rainfall of the British Islands at 36 inches annually, and the superficial area over which this rain is discharged at 120,000 square miles, then it will be found that the total quantity of rain received in one year by the British Isles is equal to about 68 cubic miles of water. If the proportion of rainfall returned to the sea by streams be taken at a third, there are 23 cubic miles; if at a fourth, there are 17 cubic miles of fresh water sent off the surface of the British Islands into the sea in one year. Assuming, in the next place, that the average ratio of mechanical impurities is only $\frac{1}{5000}$ by volume of the water, the proportion of the rainfall returned to the sea being $\frac{1}{4}$, then it will follow that $\frac{1}{8800}$ of a foot of rock is removed from the general surface of Britain every year. One foot will be planed away in 8800 years. If the mean height of the British Islands be taken at 650 feet, then, if the ratio now assumed were to continue, these islands might be levelled in about five and a half millions of years. Much more detailed observation is needed before any estimate of this kind can be based upon accurate and reliable data. But it illustrates a method of vividly bringing before the mind the reality and extent of the denudation now in progress.

### 2. *Subaerial Denudation—the unequal erosion of land.*

It is obvious that the earthy matter annually removed from the surface of the land does not come equally from the whole surface. The determination of its total quantity furnishes no aid in apportioning the loss, or in ascertaining how much each part of the surface has contributed to the total amount of sediment. On plains, watersheds, and more or less level ground, the proportion of loss may be small, while on slopes and in valleys it may be great, and it may not be easy to fix the true

[1] T. Mellard Reade, Presidential Address, Liverpool Geol. Soc. 1884-85.

ratios in these cases. But it must be borne in mind that estimates and measurements of the sum-total of denudation are not thereby affected. If we allow too little for the loss from the surface of the table-lands, we increase the proportion of the loss sustained by the sides and bottoms of the valleys, and *vice versâ*.

While these proportions vary indefinitely with the form of the surface, rainfall, &c., the balance of loss must always be, on the whole, on the side of the sloping surfaces. In order to show the full import of this part of the subject, certain ratios may here be assumed which are probably understatements rather than exaggerations. Let us take the proportion between the extent of the plains and table-lands of a country, and the area of its valleys, to be as nine to one; in other words, that, of the whole surface of the country, nine-tenths consists of broad undulating plains, or other comparatively level ground, and one-tenth of steeper slopes. Let it be further assumed that the erosion of the surface is nine times greater over the latter than over the former area, so that while the more level parts of the country have been lowered one foot, the valleys have lost nine feet. If, following the measurements and calculations already given, we admit that the mean annual quantity of detritus carried to the sea may, with some probability, be regarded as equal to the yearly loss of $\frac{1}{6000}$ of a foot of rock from the general surface of the country, then, apportioning this loss over the surface in the ratio just given, we find that it amounts to $\frac{5}{9}$ of a foot from the more level grounds in 6000 years, and 2 feet from the valleys in the same space of time. Now, if $\frac{5}{9}$ of a foot be removed from the level grounds in 6000 years, 1 foot will be removed in 10,800 years; and if 5 feet be worn out of the valleys in 6000 years, 1 foot will be worn out in 1200 years. This is equal to a loss of only $\frac{1}{12}$ of an inch from the table-lands in 75 years, while the same amount is excavated from the valleys in $8\frac{1}{2}$ years.

It may seem at first sight that such a loss as only a single line from the surface of the open country during more than the lapse of a long human life is almost too trifling to be taken into account, as it is certainly too small to be generally appreciable. In the same way, if we are told that the constant wear and tear which is going on before our eyes in valleys and water-courses does not effect more than the removal of one line of rock in eight and a half years, we may naturally enough regard such a statement as probably an under-estimate. But if we only permit the multiplying power of time to come into play, the full force of those seemingly insignificant quantities is soon made apparent. For we find by a simple piece of arithmetic that, at the rate of denudation which has been just postulated as probably a fair average, a valley of 1000 feet deep may be excavated in 1,200,000 years, a period which, in the eyes of most geologists, will seem short indeed.

Objection may be taken to the ratios from which this average rate of denudation is computed. Without attempting to decide what this average rate actually is—a question which must be determined for each region upon much fuller data than are at present available—the geologist will find advantage in considering, from the point of view now indicated, what,

according to the most probable estimates, is actually in progress around him. Let him assume any other apportioning of the total amount of denudation, he does not thereby lessen the measurement of that amount, which can be and has been ascertained in the annual discharge of rivers. A certain determined quantity of rock is annually worn off the surface of the land. If, as already remarked, we represent too large a proportion to be derived from the valleys and water-courses, we diminish the loss from the open country; or, if we make the contingent derived from the latter too great, we lessen that from the former. Under any ascertained or assumed proportion, the facts remain, that the land loses a certain ascertainable fraction of a foot from its general surface per annum, and that the loss from the valleys and water-courses is larger than that fraction, while the loss from the level ground is less.

### 3. *Marine Denudation—its comparative rate.*

From the destructive effects of occasional storms an exaggerated estimate has been formed of the relative potency of marine erosion. That the amount of waste by the sea must be inconceivably less than that effected by the subaerial agents, will be evident if we consider how small is the extent of surface exposed to the power of the waves, when contrasted with that which is under the influence of atmospheric waste. In the general degradation of the land, this is an advantage in favour of the subaerial agents which would not be counterbalanced unless the rate of waste by the sea were many thousands or millions of times greater than that of rains, frosts and streams. But in reality no such compensation exists. In order to see this, it is only necessary to place side by side measurements of the amount of work actually performed by the two classes of agents. Let us suppose, for instance, that the sea eats away a continent at the rate of ten feet in a century—an estimate which probably attributes to the waves a much higher rate of erosion than can, as the average, be claimed for them.[1] Then a slice of about a mile in breadth will require about 52,800 years for its demolition, ten miles will be eaten away in 528,000 years, one hundred miles in 5,280,000 years. Now we have already seen that, on a moderate computation, the land loses about a foot from its general surface in 6000 years, and that, by the continuance of this rate of subaerial denudation, the continent of Europe might be worn away in about 4,000,000 years. Hence, before the sea, advancing at the rate of ten feet in a century, could pare off more than a mere marginal strip of land, between 70 and 80 miles in breadth, the whole land might be washed into the ocean by atmospheric denudation.

Some such results as these would necessarily be produced if no disturbance took place in the relative levels of sea and land. But in estimating the amount of influence to be attributed to each of the denuding agents in past times, we require to take into account the com-

[1] It may be objected that this rate is far below that of parts of the east coast of England (*ante*, p. 571). But along the rocky western coast of Britain the loss is perhaps not so much as one foot in a century.

plicated effects that would arise from the upheaval or depression of the earth's crust. If frequent risings of the land, or elevations of the sea-floor into land, had not taken place in the geological past, there could have been no great thickness of stratified rocks formed, for the first continents must soon have been washed away. But the great depth of the stratified part of the earth's crust, and the abundant breaks and unconformabilities among the sedimentary masses, show how constantly, on the one hand, the waste of the land was compensated by elevatory movements, while, on the other, the continued upward growth of vast masses of sedimentary deposits was rendered possible by prolonged depression of the sea-bed.

When a mass of land is raised to a higher level above the sea, a larger surface is exposed to denudation. As a rule, a greater rainfall is the result, and consequently, also, a more active waste of the surface by subaerial agents. It is true that a greater extent of coast-line is exposed to the action of the waves, but a little reflection will show that this increase will not, on the whole, bring with it a proportionate increase in the amount of marine denudation. For, as the land rises, the cliffs are removed from the reach of the breakers, and a more sloping beach is produced, on which the sea cannot act with the same potency as when it beats against a cliff-line. Moreover, as the sea-floor approaches nearer the surface of the water, it is the former detritus washed off the land, and deposited under the sea, which first comes within the reach of the currents and waves. This serves, in some measure, as a protection to the solid rock below, and must be cut away by the ocean before that rock can be exposed anew. While, therefore, elevatory movements tend on the whole to accelerate the action of subaerial denudation, they in some degree check the natural and ordinary influence of the sea in wasting the land. Again, the influence of movements of depression will probably be found to tend in an opposite direction. The lowering of the general level of the land will, as a rule, help to lessen the rainfall, and consequently the rate of subaerial denudation. At the same time, it will aid the action of the waves, by removing under their level the detritus produced by them and heaped up on the beach, and by thus bringing constantly within reach of the sea fresh portions of the land-surface. But even with these advantages in favour of marine denudation, the balance of power will, on the whole, remain always on the side of the subaerial agents.

### 4. *Marine Denudation—its final result.*

The general result of the erosive action of the sea on the land is the production of a submarine plain. As the sea advances, the sites of successive lines of beach pass under low-water mark. Where erosion is in full operation, the littoral belt, as far down as wave-action has influence, is ground down by moving detritus. This result may often be instructively observed, on a small scale, upon rocky shores where sections like that in Fig. 180 occur. We can conceive, that, should no change of level between sea and land take place, the sea might slowly eat its way far into the land, and produce a gently sloping, yet apparently almost hori-

zontal selvage of plain, covered permanently by the waves. In such a submarine plain, the influence of geological structure, and notably of the relative powers of resistance of different rocks, would make itself conspicuous, as may be seen even on a small scale on any rocky beach (Fig. 171). The present promontories caused by the superior hardness of their component rocks would no doubt be represented by ridges on the subaqueous plateau, while the existing bays and creeks, worn out of softer rocks, would be marked by lines of valley or hollow.[1]

This tendency to the formation of a submarine plain along the margin of the land deserves special attention by the student of denudation. The angle at which a mass of land descends to the sea-level serves roughly to indicate the depth of water near shore. A precipitous coast commonly rises out of deep water; a low coast is usually skirted with shallow water, the line of slope above sea-level being in a general way prolonged below it. The belt of beach forms a kind of terrace or notch along the maritime slope. Sometimes, where the coast-line is precipitous, this terrace is nearly or wholly wanting. In other places, it runs

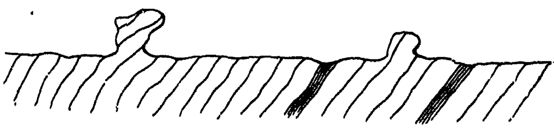


Fig. 180.—Section of Rocks ground down to a plain on the beach by wave-action.

out a good way beyond low-water mark. On a great scale, the floor of the North Sea and that of the Atlantic Ocean, for some distance to the west of Ireland, may be regarded as a marine platform that once formed part of the European continent (Fig. 181), and has been reduced by denudation and subsidence to its present position.

So far as the present *régime* of nature has been explored, it would seem to be inevitable that, unless where subterranean movements interfere, or where volcanic rocks are poured forth at the surface, a submarine plain should be formed along the margin of the land. This final result of denudation has been achieved again and again in the geological past, as is shown by the existence of table-lands of erosion (*ante*, p. 53). To these table-lands the name of "plains of marine denudation" has been applied by Sir A. C. Ramsay. From what has now been said, however, it will be seen that in their actual production the sea has really had less to do than the meteoric agents. A "plain of marine denudation" is that base-level of erosion to which a mass of land had been reduced mainly by the subaerial forces—the line below which further degradation became impossible, because the land was thereafter protected by being covered by the sea. Undoubtedly the last touches in the long process of sculpturing were given by marine waves and currents, and the surface of the plain, save

[1] Mr. Whitaker, in the excellent paper on subaerial denudation cited on p. 578, has pointed out the different results which are obtained by the subaerial forces from those of sea-action in the production of lines of cliff.

where it has subsided, may correspond generally with the lower limit of wave-action. Nevertheless, in the past history of our planet, the influence of the ocean has probably been far more conservative than destructive. Only beneath the reach of the waves can the surface of the abraded land escape the demolition which sooner or later overtakes all that rises above them.

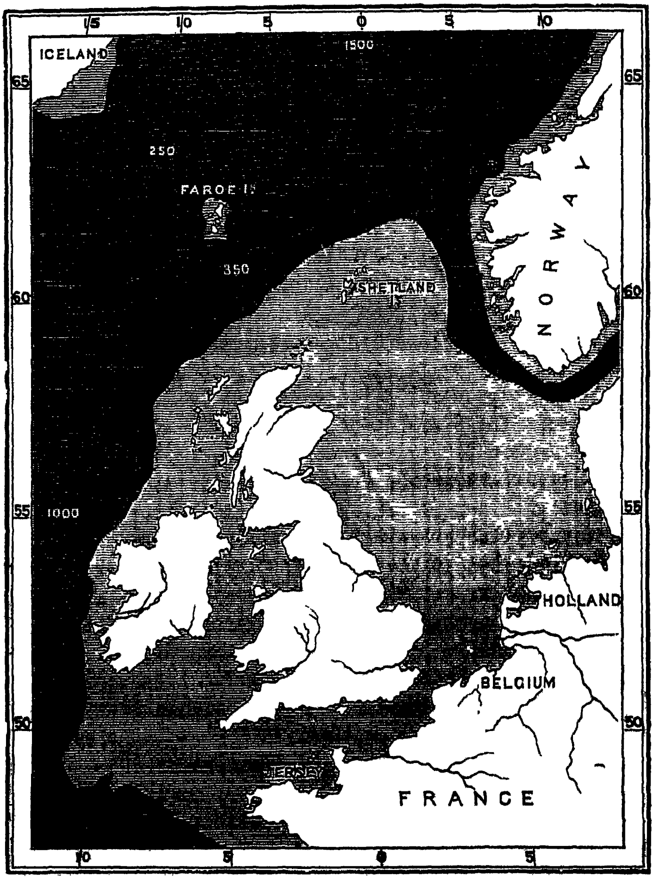



Fig. 181.—Map of British submarine platform.

The darker tint represents sea-bottom more than 100 fathoms deep, while the paler shading shows the area of less depths. The figures mark the depths in fathoms. The narrow channel between Norway and Denmark is 2580 feet deep.

## 5. *Deposition—the framework of new land.*

If a survey of the geological changes in daily progress upon the surface of the earth leads us to realise how momentously the land is being worn down by the various epigene agents, it ought also to impress us with the vast scale on which new formations—the foundation of future

land—are being continually accumulated. Every foot of rock removed from the surface of a country is represented by a corresponding amount of sedimentary material arranged somewhere beneath the sea. Denudation and deposition are synchronous and co-equal.

On land, vast accumulations of detrital origin are now in progress. Alluvial plains of every size, from those of mere brooks up to those of the largest rivers, are built up of gravel, sand and mud derived from the disintegration of higher ground. From the level of the present streams, successive terraces of these materials can be followed up to heights of several hundred feet. Over wide regions, the daily changes of temperature, moisture and wind supply a continual dust, which, in the course of centuries, has accumulated to a depth of sometimes 1500 feet, and covers thousands of square miles of the surface of the continents. The numerous lakes that dot the surface of the land serve as receptacles in which a ceaseless deposition of sediment takes place. Already an unknown number of once existent lakes has been entirely filled up with detrital accumulations, and every stage towards extinction may be traced in those that remain.

But, extensive though the terrestrial sedimentary deposits may be, they can be regarded merely as temporary accumulations of the detritus. Save where protected and concealed under the water of lakes, they are everywhere exposed to a renewal of the denudation to which they owe their origin. Only where the sediment is strewn over the sea-floor beneath the limit of breaker-action, is it permitted to accumulate undisturbed. In these quiet depths are now growing the shales, sandstones, and limestones which, by future terrestrial revolutions, will be raised into land, as those of older times have been. Between the modern deposits and those of former sea-bottoms which have been upheaved, there is the closest parallel. Deposition will obviously continue as long as denudation lasts. The secular movements of the crust seem to have been always sufficiently frequent and extensive to prevent cessation of these operations. And so we may anticipate that it will be for many geological ages yet to come. Elevation of land will repair what has been lost by superficial waste, and subsidence of sea-bottom will provide space for the continued growth of sedimentary deposits.

## Section iii. Life.

Among the agents by which geological changes are now, and have in past time been, effected upon the earth's surface, living organisms take by no means an unimportant place. They serve as a vehicle for continual transferences from the atmosphere into the mineral world, and from the mineral world back into the atmosphere. Thus, they decompose atmospheric carbon-dioxide, and in this process have gradually removed from the atmosphere the vast volumes of carbon now locked up within the earth's crust in beds of solid coal. By their decomposition, organic acids are produced which partly enter into mineral combinations, and partly return to the atmosphere as carbon-dioxide. Plants abstract

from the soils silica, alkalies, calcium-phosphate and other mineral substances, which enter largely into the composition of the hard parts of animals. On the death and decomposition of animals, these substances are once more relegated to the inorganic world, thence to enter upon a new circulation through the tissues of living organisms.

From a geological point of view, the operations of organic life may be considered under three aspects—destructive, conservative and reproductive.

## § 1. Destructive Action.

**Plants** in several ways promote the disintegration of rocks.

1. By keeping the surfaces of rocks moist, plants provide means for the continuous solvent action of water. This influence is particularly observable among liverworts, mosses and similar moisture-loving plants.

2. By their decay, plants supply an important series of organic acids, which exert a powerful influence upon soils, minerals and rocks. The humus, or organic portion of vegetable soil, consists of the remains of plants and animals in all stages of decay, and contains a complex series of organic compounds still imperfectly understood. Among these are humic, azo-humic, ulmic, crenic and apocrenic acids.[1] The action of these organic acids is twofold. (1) From their tendency to oxidation, they exert a markedly reducing influence (*ante*, pp. 451, 469, 582). Thus they convert metallic sulphates into sulphides, as in the blue marine muds, and the abundant pyritous incrustations of coal-seams, shell-bearing clays, and even sometimes of mine-timbers. Metallic salts are still further reduced to the state of native metals. Native silver occurs among silver ores in fossil wood among the Permian rocks of Hesse. Native copper has been frequently noticed in the timber-props of mines; it was found hanging in stalactites from the timbers of the Ducktown copper mines, Tennessee, when the mines were re-opened after being shut up during the civil war. Fossil fishes from the Kupferschiefer have been incrusted with native copper, and fish-teeth have been obtained from Liguria completely replaced by this metal. (2) They exert a remarkable power of dissolving mineral substances.[2] This phase of their activity has probably been undervalued by geologists. Experiments have shown that many of the common minerals of rocks are attacked by organic acids.[3] There is reason to believe that in the decomposition effected by meteoric waters, and usually attributed mainly to the operation of carbonic acid, the initial stages of attack are due

[1] See J. Roth, 'Allgemeine und chemische Geologie,' 1883, p. 596.

[2] Professor Sollas has noticed the formation of minute hemispherical pits on limestone by the solvent action of a lichen, *Verrucaria rupestris* (*Brit. Assoc.* 1880, Sects. p. 586). See also J. G. Goodchild, *Geol. Mag.* 1890, p. 464.

[3] This has been strongly insisted upon by A. A. Julien in a memoir on the "Geological Action of the Humus Acids," *Amer. Assoc.* 1879, p. 311. See also P. Thenard (*Compt. rend.* lxx. 1870, p. 1412), who shows that when the humic acids, by absorbing nitrogen from the air, become azo-humic, the latter possess a much higher solvent action on silica, combining with as much as from 7 to 24 per cent. C. W. Hayes, *Bull. Geol. Soc. Amer.* viii. (1897), p. 213.

to the powerful solvent capacities of the humic and azo-humic acids.[1] Owing, however, to the facility with which these acids pass into higher states of oxidation, it is chiefly as carbonates that the results of their action are carried down into deeper parts of the crust or brought up to the surface. Although carbonic acid is no doubt the final condition into which these unstable organic acids pass, yet during their existence they attack not merely alkalies and alkaline earths, but even dissolve silica. The relative proportion of silica in river-waters has been referred to the greater or less abundance of humus in their hydrographical basins,[2] the presence of a large percentage of silica being a concomitant of a large proportion of organic matter. Further evidence of the important influence of organic acids upon the solution of silica is supplied by many siliceous deposits (p. 612).

Wherever a layer of humus has spread over the surface of the land, traces of its characteristic decompositions may be found in the soils, subsoils and underlying rocks. Next the surface, the normal colour of the subsoils is usually changed by oxidation and hydration into tints of brown and yellow, the lower limit of the weathered zone being often sharply defined. Where the humus acids can freely attack the hydrated peroxide of iron, they remove it in solution, and the decomposed rock or soil is thereby bleached. This may be observed where pine-trees grow on ferruginous sand, a rootlet one-sixth of an inch in diameter being by its decay capable of whitening the sand to a distance of from one to two inches around it.[3] It has recently been proposed to ascribe mainly to the operation of the humus acids the thick layer of decomposed rock above noticed (p. 458) as observable so frequently south of the limits of the ice of the Glacial period, and the inference has been drawn that, even where the surface is now comparatively barren, the mere existence of this thick decomposed layer affords a presumption that it once underlay an abundant vegetation, such as a heavy primeval forest-growth.[4] Nor is the chemical action confined to the superficial layers. The organic acids are carried down beneath the surface, and initiate that series of alterations which carbonic acid and the alkaline carbonates effect among subterranean rock-masses (pp. 470, 474).

Besides giving rise to the formation of organic acids, plants appear to possess a property of nitrification whereby the decay of rocks is promoted. Certain bacteria are believed to have the power of decomposing carbonate of ammonium, abstracting the carbon and liberating nitric acid. An instance of the action is given from the Pic Pourri in the French Pyrenees, where the calcareous schists are rotten all over the surface and are permeated by the nitrifying bacteria. The nitrogen, however, is probably soon again abstracted by growing vegetation.

[1] Professor H. C. Bolton has experimented on the action of citric acid (*ante*, p. 117) on 200 different mineral species, and he finds that this organic acid possesses a power of dissolving minerals only slightly less than that of hydrochloric acid. *Brit. Assoc.* 1880, Sects. p. 505.

[2] Sterry Hunt's 'Chemical and Geological Essays,' pp. 126-150.

[3] Kindler, *Poggend. Annal.* xxxvii. (1836), p. 203. J. A. Phillips, 'Ore Deposits,' 1884, p. 14.

[4] Julien, *Amer. Assoc.* 1879, p. 378.

Ammonium sulphate and sodium chloride, when in solution in water, as in that of soils, promote the rapid decay of felspars.[1]

3. Plants insert their roots or branches between the joints of rock, or penetrate beneath the soil. Two marked effects are traceable to this action. In the first place, large slices of rock may be wedged off from the sides of wooded hills or cliffs. Even among old ruins, an occasional sapling ash or elm may be found to have cast its roots round a portion of the masonry, and to be slowly detaching it from the rest of the wall. In the second place, the soil and subsoil are opened up to the decomposing influences of the air and descending water. The distance to which, under favourable circumstances, roots may penetrate downward is much greater than might be supposed. Thus in the loess of Nebraska the buffalo-berry (*Shepherdia argophylla*) has been observed to send a root 55 feet down from the surface, and in that of Iowa the roots of grasses penetrate from 5 to 25 feet.[2]

4. By attracting rain, as thick forests, woods and mosses, more particularly on elevated ground, are believed to do, plants accelerate the general scouring of a country by running water. The indiscriminate destruction of the woods in the Levant has been assigned, with much plausibility, as the main cause of the present desiccation of that region.[3]

5. Living plants promote the decay of diseased and dead plants and animals, as when fungi overspread a damp rotting tree or the carcase of a dead animal.

**Animals.**—The destructive influences of the animal kingdom likewise show themselves in several distinct ways.

1. The surface-soil is moved, and exposed thereby to attack by rain, wind, &c. As Darwin showed, the common earth-worm is continually engaged in bringing up the fine particles of soil to the surface. He found that in fifteen years a layer of burnt marl had been buried under 3 inches of loam, which he attributed to this operation.[4] It has been already pointed out that part of the growth of soil may be due to wind-action (*ante*, p. 438). There can be no doubt, however, that the materials of vegetable soil are largely commingled and fertilised by the earth-worm, and in particular that, by being brought up to the surface, the fine particles are exposed to meteoric influences, notably to wind

[1] See Muntz, *Compt. rend.* cx. (1890), p. 1370, and authorities cited by him. On the fixation of free nitrogen by plants in the soil, see J. B. Lawes and H. Gilbert, *Journ. Roy. Agricult. Soc. Eng.* 3rd ser. vol. ii. part iv. pp. 657-702 (1892).

[2] Aughey's 'Physical Geography and Geology of Nebraska,' 1880, p. 275.

[3] See on this disputed question the works cited by Rolleston, *Journ. Roy. Geog. Soc.* xlix. (1879). The practical methods for combating the destructive action of running water are treated of in P. Demontzey's work, 'L'Extinction des Torrents en France par le Reboisement,' 2 vols. text and plates, 1895. The destruction of forests is alleged to increase the number and severity of hailstorms. Information regarding the forests of the United States will be found in the *20th Ann. Rep. U. S. G. S.* 1900, part v. p. 498.

[4] *Trans. Geol. Soc.* v. p. 505, "Vegetable Mould," 1881. Compare also the paper by Mr. Horace Darwin, "On the small Vertical Movements of a Stone laid on the Surface of the Ground," *Proc. Roy. Soc.* lxviii. (1901), p. 253.

and rain. Even a grass-covered surface may thus suffer slow denudation. Lob-worms on sandy shores possibly aid transport by waves and tides, inasmuch as they bring up large quantities of fresh sand.[1]

Burrowing animals, by throwing up the soil and subsoil, expose these to be dried and blown away by the wind. At the same time, their subterranean passages serve to drain off the superficial water, and to injure the stability of the surface of the ground above them. In Britain, the mole and rabbit are familiar examples. In North America, the prairie-dog and gopher have undermined extensive tracts of pasture-land in the west. In Cape Colony, wide areas of open country seem to be in a constant state of eruption from the burrowing operations of multitudes of *Bathyergi* and *Chrysochloris*—small mole-like animals which bring up the soil and bury the grassy vegetation under it. The decomposition of animal remains produces chemical changes similar to those resulting from the decay of plants.

2. The flow of streams is sometimes interfered with, or even diverted, by the operations of animals. Thus the beaver, by cutting down trees (sometimes 1 foot or more in diameter) and constructing dams with the stems and branches, checks the flow of water-courses, intercepts floating materials, and sometimes even diverts the water into new channels. This action is typically displayed in Canada and in the Rocky Mountain regions of the United States. Thousand of acres in many valleys have been converted into lakes, which, intercepting the sediment carried down by the streams, and being likewise invaded by marshy vegetation, have subsequently become morass and finally meadow-land. The extent to which, in these regions, the alluvial formations of valleys have been modified and extended by the operations of the beaver, is almost incredible. The embankments of the Mississippi are sometimes weakened to such an extent by the burrowings of the cray-fish as to give way and allow the river to inundate the surrounding country. Similar results have happened in Europe from the subterranean operations of rats.

3. On the western prairies of North America herds of large animals frequent the shallow wind-formed basins, which become almost the only receptacles of water in some regions. Wading into or wallowing in these pools, the animals become coated with mud, which they carry away adhering to their bodies until it drops off or dries and is rubbed away. By this means those lakes have, no doubt, been permanently deepened.[2]

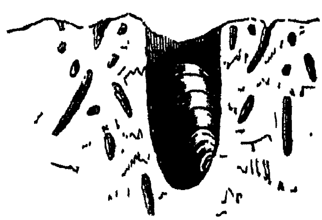


Fig. 182.—Shell-borings in limestone.

4. Some mollusks (*Pholas*, *Saxicava*, *Teredo*, &c., Fig. 182) bore into stone or wood, and by the number of contiguous perforations greatly weaken the materials. Pieces of driftwood

[1] Dr. Davison estimates the amount to be sometimes nearly 2000 tons annually over an acre. *Geol. Mag.* 1891.

[2] G. K. Gilbert, *Journ. Geol.* iii. (1895), p. 49.

are soon riddled with long holes by the teredo; while wooden piers, and the bottoms of wooden ships, are often rapidly perforated. Saxicavous shells, by piercing stone and leaving open cavities for rain and sea-water to fill, promote its decay. A potent cause of the destruction of coral-reefs is to be found in the borings of mollusks, annelids and echinoderms, whereby masses of coral are weakened so as to be more easily removed by breakers. Similar effects have been observed to be produced by snails. The hard limestone of Sulies-du-Salat, in the Haute Garonne, is abundantly pitted with cylindrical perforations about an inch broad and nearly six inches deep, made by *Helix nemoralis* and *H. hortensis.* The rock is thus honeycombed with cavities, which promote its decay by the other agents of degradation.[1]

5. Many animals exercise a ruinously destructive influence upon vegetation. Of the various insect-plagues of this kind it will be enough to enumerate the locust, phylloxera, and Colorado beetle. The pasture in some parts of the south of Scotland has in recent years been much damaged by mice, which have increased in numbers owing to the indiscriminate shooting and trapping of owls, hawks and other predaceous creatures. Grasshoppers cause the destruction of vegetation in some parts of Wyoming and other Western Territories of the United States. Animals likewise destroy each other, often on a great scale. Thus the occasional enormous development of the protozoon genera *Peridinium* and *Glenodinium* kills off the oysters and other mollusks in the waters of Port Jackson.[2] Various animals, in the process of digestion, triturate the calcareous organisms which they swallow, and in voiding the remains furnish calcareous materials to marine deposits.[3]

## § 2. Conservative Action.

**Plants.**—The protective influence of vegetation is well known.

1. The formation of a stratum of turf protects soil and rocks from being rapidly removed by rain or wind. Hence the surface of a district so protected is denuded with extreme slowness, except along the lines of

[1] E. Harlé, *B. S. G. F.* xxviii. (1900), p. 204.

[2] An occurrence of this kind in March 1891 led to an almost complete destruction of the oysters, mussels and other bivalves; the rest of the littoral fauna—limpets and other univalves, starfish, worms, ascidians and other lower forms of life—were so seriously affected that dead and dying were strewn about in great numbers, while the higher forms, able to move rapidly, had retired to deep water. T. Whittelegge, *Records of Australian Museum*, i. No. 9 (1891), p. 179.

[3] The triturating action of annelids and other marine creatures upon the minute calcareous organisms which pass through their intestines is well illustrated by some ancient formations. It is evident that what are now extensive masses of solid limestone and dolomite, once existed as fine calcareous silt, the greater part of which has been swallowed and voided by worms. The Cambrian rocks of Durness, in the north-west of Scotland, furnish a notable example of this action. Not only is the material comminuted, but, as J. Y. Buchanan has shown (*ante*, p. 582), it sometimes undergoes chemical change, as where the sulphates in sea-water are reduced to sulphides and the blue mud of the sea-bottom acquires its distinctive character.

its water-courses. A crust of lichens doubtless on the whole protects the rock underneath it from atmospheric agents.[1]

2. Many plants, even without forming a layer of turf, serve by their roots or branches to protect the loose sand or soil on which they grow from being removed by wind. The common sand-carex and other arenaceous plants bind littoral sand-dunes, and give them a permanence which would at once be destroyed were the sand laid bare again to the storms. In North America, the sandy tracts of the Western Territories are in many places protected by the sage-brush and grease-wood. The growth of sedges, reeds, shrubs and brushwood along the course of a stream not only keeps the alluvial banks from being so easily undermined and removed as would otherwise be the case, but serves to arrest the sediment in floods, filtering the water, and thereby adding to the height of the flood-plain. On some parts of the west coast of France, extensive ranges of sand-hills have been planted with pinewoods, which, while preventing the destructive inland march of the sand, also yield a large revenue in timber, and have so influenced the climate as to make these districts a resort for pulmonary invalids.[2] In tropical countries, the mangrove grows along the sea-margin, and not only protects the land, but adds to its breadth, by forming and increasing a maritime alluvial belt.

3. Some marine plants likewise afford protection to shore rocks. This is done by the hard incrustation of calcareous nullipores; likewise by the tangles and smaller fuci which, growing abundantly on the littoral zone, break the force of waves, or diminish the effects of ground-swell.

4. Forests and brushwood protect soil, especially on slopes, from being washed away by rain. This is shown by the disastrous results of the thoughtless destruction of woods. According to Reclus,[3] in the three centuries from 1471 to 1776, the "vigueries," or provostry-districts of the French Alps, lost a third, a half, and even three-fourths of their cultivated ground, and the population has diminished in somewhat similar proportions. From 1836 to 1866 the departments of Hautes and Basses Alpes lost 25,000 inhabitants, or nearly one-tenth of their population—a diminution which has with plausibility been assigned to the reckless removal of the pine-forests, whereby the steep mountain-sides have been washed bare of their soil. The desiccation of the countries bordering the eastern Mediterranean has been ascribed to a similar cause.[4]

[1] But see the remark already made, *ante*, p. 598, note 2.

[2] De Lavergne, 'Économie rurale de la France depuis 1789,' p. 297. *Edin. Review*, Oct. 1864, article on Coniferous Trees.

[3] 'La Terre,' i. p. 410. J. C. Brown, 'Reboisement en France,' London, 1876. According to Dr. J. Carret, however, the deterioration of the climate of Savoy and the diminution of the population there cannot be attributed to deboisement. The cutting-down of the forests dates from the First Empire, but replanting has been going on for some time, and the forest area is now a little larger than it was last century. Nevertheless, the depopulation of the higher tracts, which had begun before last century, continues, notwithstanding the replanting of the slopes: *Assoc. Française*, 1879, p. 588.

[4] Recent attempts to reclothe the desiccated stone-wastes of Dalmatia with trees have

5 In mountain districts, pine-forests exercise also an important conservative function in preventing the formation or arresting the progress of avalanches. In Switzerland, some of the forests which cross the lines of frequent snow-falls are carefully preserved.

**Animals** do not on the whole exert an important conservative action upon the earth's surface, save in so far as they form new deposits, as will be immediately referred to. On many shores, however, by thickly encrusting rocks, they act like the marine vegetation above alluded to, and protect these to a considerable extent from abrasion by the waves. The most familiar example in Europe of this action is that of the common acorn-shell or barnacle (*Balanus balanoides*). Serpulæ often encrust considerable masses of a coral reef, and act like nullipores, in protecting decaying and dead corals from being so rapidly broken up by the waves as they would otherwise be. But even soft-bodied animals, such as sponges and ascidians, when they spread over rocks near low-water, afford protection from at least the less violent attacks of the breakers. Professor Herdman, who has called attention to this subject, enumerates as the more important animals in protecting shore rocks: Foraminifera (such as *Planorbulina vulgaris*), calcareous and fibrous sponges, hydroid zoophytes, sea anemones, corals, annelids (serpula), polyzoa, cirripedes, mollusks (such as gregarious forms like the mussel and oyster, and gasteropods like the limpet), and simple and compound ascidians.[1]

In the prairie regions of Wyoming and other tracts of North America, some interesting minor effects are referable to the herds of roving animals which migrate over these territories. The trails made by the bison, the elk and the big-horn or mountain sheep, are firmly trodden tracks on which vegetation will not grow for many years. All over the region traversed by the now nearly extinct bison, numerous circular patches of grass used to be seen which were formed on the hollows where this animal had wallowed. Originally they were shallow depressions, formed in great numbers where a herd of bisons had rested for a time. On the advent of the rains they become pools of water; thereafter grasses spring up luxuriantly, and so bind the soil together that these grassy patches, or "bison-wallows," may actually become slightly raised above the general level, if the surrounding ground becomes parched and degraded by winds.[2] It is possible that, in some cases, these hollows may be dried up and be deepened by the action of wind, so as to become part of the series of wind-formed basins already referred to (pp. 437, 519).

## § 3. Reproductive Action.

**Plants.**—Both plants and animals contribute materials towards new geological formations, chiefly by the aggregation of their remains, partly from their chemical action. Their remains are likewise enclosed in

been attended with success. See Mojsisovics, *Jahrb. Geol. Reichsanst.* 1880, p. 210; also the work of Demontzey, cited on p. 600.

[1] *Proc. Liverpool Geol. Soc.* 1884-85.

[2] Comstock, in Captain Jones's 'Reconnaissance of N.W. Wyoming,' 1875, p. 175.

deposits of sand and mud, the bulk of which they thus help to increase. Of plant-formations the following illustrative examples may be given :—

1. Sea-weeds.—It was long ago shown by Forchhammer that fucoids abstract an appreciable amount of lime, magnesia, soda and other components of sea-water, and he believed that these plants probably played an important part in the accumulation of the older Palæozoic sediments.[1] Some marine algæ abstract calcium-carbonate from sea-water and build it up into their own substance. A nullipore (*Lithothamnium nodosum*) has been found to contain about 84 per cent of calcium-carbonate, 5½ of magnesium-carbonate, with a little phosphoric acid, alumina and oxides of iron and manganese.[2] Hence the calcareous nullipores which encrust shore rocks provide solid material which, either growing *in situ* or broken off and distributed by the waves, gives rise to a distinct geological deposit. Considerable masses of a structureless limestone are formed in the Bay of Naples mainly by calcareous algæ. By the infiltration of water into the dead parts of the material the organic structure is destroyed.[3] There can be no doubt that from the Palæozoic period to the present day an important part has been taken by calcareous algæ in the formation of thick and extensive masses of limestone, such as the Tertiary Lithothamnium-limestone (Leitha-kalk) of the Vienna basin, and the Triassic Gyroporella-limestone of the Bavarian and Tyrolese Alps.[4]

2. Lake-plants.—In fresh-water lakes also considerable accumulations of calcareous marl are formed by plants that secrete lime within their cells. Of these plants those of the stone-wort or *Chara* tribe are most familiar in temperate latitudes. Thus in the lakes of the Jura the species of *Chara* flourish predominantly at a depth of from 8 to 12 metres, and form there an extremely luxuriant vegetation.[5] In the Würmsee or Starnbergersee of Upper Bavaria the Chara-zone extends from 2 to about 7 metres down.[6] In the lakes of Michigan, which are remarkable for their extensive deposits of marl, the *Chara* has a similar range. In some lakes the calcareous material aggregated by plants is increased by the addition of the shells of fresh-water mollusks and ostracods.[7] The action of bog-mosses and other plants in forming calc-sinter is described on p. 611.

3. Humus, Black Soils, &c.—Long-continued growth and decay of vegetation upon a land-surface not only promotes disintegration of the superficial rock, but produces an organic residue, the intermingling of which with mineral débris constitutes vegetable soil. Undisturbed through long ages, this process has, under favourable conditions, given

[1] *Brit. Assoc.* 1844, p. 155.

[2] Gümbel, *Abhandl. Bayerisch. Akad. Wissensch.* xi. 1871.

[3] J. Walther, *Z. D. G. G.* xxxvii. (1885), p. 329.

[4] See Hill, *Q. J. G. S.* xlvii. (1891), pp. 243 and 602; Gregory, xlviii. (1892), p. 538; Hinde, xlix. (1893), p. 230; Rothpletz, *Z. D. G. G.* xliii. (1891).

[5] Magnin, *Compt. rend.* cxvi. pp. 535, 905.

[6] F. Brand, *Botan. Centralbl.* lxv. (1896), p. 1 *et seq.*

[7] C. A. Davis, "Natural History of Marl," *Journ. Geol.* viii. (1900), pp. 485, 498, and ix. (1901), p. 491.

rise to thick accumulations of a rich dark loam. Such are the "regur," or rich black cotton soil of India; the "tchernozom," or black earth of Russia, containing from 6 to 10 per cent of organic matter; and the deep fertile soil of the American prairies and savannahs. These formations cover plains many thousands of square miles in extent. The "tundras" of northern latitudes are frozen plains of which the surface is covered with arctic mosses and other plants.[1]

4. Peat-mosses and Bogs.[2]—In temperate and arctic latitudes, marshy vegetation accumulates *in situ* to a depth of sometimes 40 or 50 feet, in what are termed bogs or peat-mosses. In Northern Europe and America these vegetable deposits have been largely formed by mosses, especially species of *Sphagnum*, which, growing on hill-tops, slopes and valley-bottoms as a wet spongy fibrous mass, die in their lower parts and send out new fibres above.[3] Some peaty deposits have been formed in lakes, either by the growth of aquatic plants on the bottom, or by the precipitation of decaying vegetation from the layer of matted plant-growth which creeps from shore along the surface of the water.[4] Occasionally these vegetable accumulations become detached, and form what are popularly known as floating islands.[5] In some cases, peat

[1] For a full account of the Tchernozom, see Sibirtzew's large memoir already cited (*ante*, p. 460), from p. 96 to p. 106, and the table at the end; Hume, *Geol. Mag.* 1894, pp. 303, 349; and a pamphlet, 'Über den Humus,' by Dr. Von Ollech, Berlin, 1890. It may be well to take note here again of the extensive accumulation of red loam in limestone regions which have long been exposed to atmospheric influences. To what extent vegetation may co-operate in the production of this loam, has not been determined. Fuchs believes that the "terra rossa" is only present in dry climates where the amount of humus is small (*ante*, p. 457, and authorities there cited).

[2] For a general account, see T. R. Jones, *Proc. Geol. Assoc.* vi. (1880), p. 207. On the composition, structure and history of peat-mosses, consult Rennie's 'Essays on Peat-moss,' Edinburgh, 1810; Steele's 'Natural and Agricultural History of Peat-moss,' Edinburgh, 1826; Templeton, *Trans. Geol. Soc.* v. p. 608; H. Schinz-Gessner, 'Der Torf, &c.,' Zurich, 1857; Pokorny, *Verhand. Geol. Reichsanst.*, Vienna, 1860; Senft, 'Humus-, Marsch-, Torf-, und Limonit-bildungen,' Leipzig, 1862; G. Thenius, 'Die Torfmoore Oesterreichs,' Vienna, 1874; J. Geikie, *Trans. Roy. Soc. Edin.* xxiv. p. 363. For a list of plants that supply material for the formation of peat, see J. Macculloch's 'Western Islands,' vol. i.; T. R. Jones, above quoted; J. Früh, "Kritische Beiträge zur Kenntniss des Torfes," *Jahrb. Geol. Reichsanst.* xxxv. (1885), p. 677; *Bull. Soc. Botan. Suisse*, i. (1891); W. Fream, *Journ. Roy. Agric. Soc. England*, 3rd ser. vol. iv. part iv. (1894). A valuable paper on the peat-mosses of Norway, their distribution, area, enclosed plant-remains and geological age, will be found under the title of "Om Torfmyrer i Norge," by G. E. Stangeland, *Norges Geol. Undersög*, No. 20, 1896, and No. 24, 1897; G. Andersson, 'Finlandstorfmossur'; J. Holmboe, *Geol. Fören. Stockholm*, xxii. (1900), p. 55, gives sections of two Norwegian peat-mosses, with the vegetation of each layer. For methods of collecting and investigating the materials of peat-mosses, see Book V. Sect. vi.

[3] Certain bacteria are believed by some botanists to exert much influence in the conversion of vegetation (cellulose) into peat, lignite and coal. See on the transformation of plants into combustible minerals, L. Lemière, *Compt. rend. Congrès Géol. Internat. Paris*, 1900, p. 502; B. Renault, p. 646 (C. E. Bertrand, p. 458).

[4] For accounts of matted vegetation covering lakes, see *Land and Water*, 1876, pp. 180, 282.

[5] Such floating islands are of frequent occurrence among the Scandinavian lakes. For

may possibly have risen in brackish-water conditions. There are even instances cited of marine peat formed of sea-weeds (*Zostera*, *Fucus*, &c.).[1] Among the Alps, as also in the northern parts of South America, and among the Chatham Islands, east of New Zealand, various phanerogamous plants form on the surface a thick stratum of peat.

A succession can sometimes be detected in the vegetation out of which the peat has been formed. Thus in Europe, among the bottom layers traces of rush (*Juncus*), sedge (*Iris*), and fescue-grass (*Festuca*) may be observed, while not infrequently an underlying layer of fresh-water marl, full of mouldering shells of *Limnea*, *Planorbis* and other lacustrine mollusks, with traces of *Chara*, shows that the area was originally a lake which has been filled up with vegetation. The next and chief layer of the peat will usually be found to consist mainly of matted fibres of different mosses, particularly

Fig. 183.—View of Scottish Peat-moss opened for digging fuel.

*Sphagnum*, *Polytrichum* and *Bryum*, mingled with roots of coarse grasses and aquatic plants. The higher layers frequently abound in the remains of heaths. Every stage in the formation of peat may be observed where mosses are cut for fuel; the portions at the bottom are more or less compact, dark brown or black, with comparatively little external appearance of vegetable structure, while those at the top are loose, spongy and fibrous, where the living and dead parts of the mosses commingle (Fig. 183).

It frequently happens that remains of trees occur in peat-mosses. Sometimes the roots are imbedded in soil underlying the moss, showing that the moss has formed since the growth of the trees (see p. 438). In other cases, the roots and trunks occur in the heart of the peat, proving that the trees grew upon the mossy surface, and were finally, on their decay, enclosed in growing peat (Fig. 184). A succession of trees has been observed among the Danish peat-mosses, the Scotch fir (*Pinus sylvestris*) and white birch (*Betula*

examples, see V. Oberg, *Geol. Fören. Stockholm*, xii. (1890), p. 422; xvi. (1894), p. 96; R. Sieger, *op. cit.* xvi. p. 231; E. Svedmark, p. 347; C. A. Lindvall, p. 438.

[1] J. Macculloch, 'System of Geology,' 1831, vol. ii. p. 341. Sirodot, *Compt. rend.* lxxxvii. (1878), p. 267. Bobierre, *Ann. Mines*, 7me sér. x. (1876), p. 469. J. G. Goodchild, *Geol. Mag.* 1900, p. 381.

*alba*) being characteristic of the lower layers; higher portions of the peat being marked by remains of the oak, while at the top comes the common beech. Remains of the same kinds of trees are abundant in the bogs of Scotland and Ireland.

The rate of growth of peat varies within wide limits. An interesting example of the formation and growth of peat-moss in the latter half of the seventeenth century is on record.[1] In the year 1651 an ancient pine-forest occupied a level tract of land among the hills in the west of Ross-shire. The trees were all dead, and in a condition to be blown down by the wind. About fifteen years later every vestige of a tree had disappeared, the site being occupied by a spongy green bog into which a man would sink up to the arm-pits. Before the year 1699 the tract had become firm enough to yield good peat for fuel. In the valley of the Somme, three feet of peat will grow in from 30 to 40 years.[2] On a moor in Hanover, a layer of peat from 4 to 9 feet thick formed in about

Fig. 184.—Scene in a Sutherland Peat-moss.

30 years. Near the Lake of Constance, a layer of 3 to 4 feet grew in 24 years. Among the Danish mosses, a period of 250 to 300 years has been required to form a layer 10 feet thick. Much must depend upon the climate, slope, drainage and soil. Some European peat-mosses are probably of extreme antiquity, having begun to form soon after the surface was freed from the snow and ice of the glacial period. In the lower parts of these mosses, traces of the arctic flora which then overspread so much of the continent are to be met with. In other instances, the mosses are at least as late as Roman times.[3] Change of climate and likewise of drainage may stop the formation of peat, so that shrubs and trees spring up on the firm surface. Along the Flemish coast a layer of peat

[1] Earl of Cromarty, *Phil. Trans.* xxvii.

[2] J. Kolb, *Proc. Inst. Civ. Engin.* xl. (1875), p. 35.

[3] On mosses of Flanders and north of France, see H. Debray, *Bull. Soc. Géol. France*, 3me sér. ii. p. 46. *Ann. Soc. Géol. Nord*, 1870-74, p. 19. Lorié, *Arch. Mus. Teyler*, 2me sér. iii. part 5 (1890), pp. 423, 439. Below the moors of Oldenburg, Roman coins, weapons and plank-roads are found at a depth of 13 feet and upwards (*Petermann's Mittheil.* 1888, v.). On the Bohemian peat-bogs, see F. Sitensky, *Archiv Landesdurchforsch. Böhmen*, vi. (1891); on those lying east of the Christiania Fjord, G. E. Stangeland in the memoir cited *ante*, p. 606; on those of Schleswig-Holstein, R. v. Fischer-Benzon, *Abh. Naturwiss. Ver. Hamburg*, xi. (1891).

containing mosses, rushes, and other fresh-water plants, underlies four or five feet of clays and sands with marine shells, indicating a subsidence and re-elevation of the country.[1]

Peat-mosses occupy many thousand square miles of Europe and North America.[2] About one-seventh of Ireland is covered with bogs, that of Allen alone comprising 238,500 acres, with an average depth of 25 feet. Where lakes are gradually converted into bogs, the marshy vegetation advances from the shores, and sometimes forms a matted treacherous green surface, beneath which the waters of the lake still lie. The decayed vegetable matter from the under part of this crust sinks to the bottom of the water, forming there a fine peaty mud, which slowly grows upward. Eventually, as the spongy covering spreads over the lake, a layer of brown muddy water may be left between the still growing vegetation above and the muddy deposit at the bottom. Heavy rains, by augmenting this intermediate watery layer, sometimes make the centre swell up until the matted skin of moss bursts, and a deluge of black mud pours into the surrounding country. The inundated ground is covered permanently with a layer of black peaty earth.[3]

From the treacherous nature of their surface, peat-mosses have frequently been the receptacles for bodies of men and animals that ventured upon them. As peat possesses great antiseptic power, these remains are usually in a state of excellent preservation. In Ireland, skeletons of the extinct large Irish elk (*Megaceros hibernicus*) have been dug up from many of the bogs. Human weapons, tools, and ornaments have been exhumed from peat-mosses; likewise crannoges, or pile-dwellings (constructed in the original lakes that preceded the mosses), and canoes hollowed out of single trees.

5. Mangrove-swamps.—On the low moist shores and river-mouths of tropical countries, the mangrove-tree plays an important geological part. It grows in such situations in a dense jungle, sometimes twenty miles broad, which fringes the coast as a green selvage, and runs up, if it does not wholly occupy, creeks and inlets. The mangrove flourishes in sea-water, even down to low-water mark, forming there a dense thicket, which, as the trees drop their radicles and take root, grows outward into the sea. It is singular to find terrestrial birds nestling in the branches above, and crabs and barnacles living among the roots below. By the network of subaqueous radicles and roots, the water that flows off the land is filtered of its sediment, which, retained among the vegetation, helps to turn the spongy jungle into a firm soil.[4] On the coast of Florida, the mangrove-swamps stretch for long distances, as a belt from five to twenty miles broad, which winds round the creeks and inlets. At Bermuda, the mangroves co-operate with grasses and other plants to choke up the creeks and brackish lakes. In these waters calcareous algæ abound, and, as their remains are thrown up amidst the sand and vegetation, they form a remarkably calcareous soil (pp. 161, 443).[5]

6. Siliceous Sinter, Diatom-earth or Ooze.—Various algæ (Diatoms) and some bog-mosses (*Hypnum*) can flourish in the hot water of thermal springs and abstract from it a jelly of silica, which on drying

[1] *Ann. Mines*, 7me sér. x. p. 468.

[2] For an account of the fresh-water morasses and swamps of the United States, see N. S. Shaler, *10th Ann. Rep. U. S. G. S.* 1890, p. 255.

[3] For a recent example, see *Nature*, lv. (1897), pp. 254, 268.

[4] The growth of mangrove swamps is described by Professor Shaler in the *Annual Report* of the Geological Survey cited above, p. 291.

[5] See Nelson, *Q. J. Geol. Soc.* ix. p. 200 *et seq.*; J. J. Rein, *Bericht Senckenb. Naturf. Ges.* 1872-73, p. 139; Wyville Thomson's 'Atlantic,' i. p. 290 (*ante*, pp. 161, 443).

generally becomes a loose pulverulent sinter, though evaporation of the water may harden it into a firm mass. The most familiar accumulations of this nature now in course of formation are probably those of the warm water marshes supplied by the hot springs of the Yellowstone Park, where the oozy deposits and drier meadows cover many square miles, sometimes to a depth of six feet.[1] Waters which contain too small a proportion of silica to deposit sinter of themselves, may thus become an abundant source of this material through the operation of diatoms and bog-mosses.[2] "Infusorial" earth and "tripoli powder" consist mainly of the frustules and fragmentary débris of diatoms, which have accumulated on the bottoms of lacustrine areas, the purer varieties containing 90 to 97 per cent of silica. They form beds sometimes 50 feet thick, which may be cemented into a flint-like substance by the solution and re-deposit of some of the silica. (Richmond, Virginia;

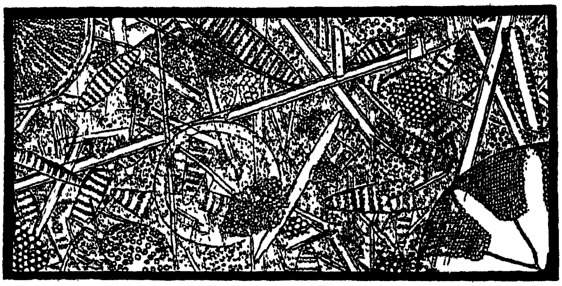


Fig. 185.—Diatom ooze dredged up by the *Challenger* Expedition from a depth of 1950 fathoms in the Antarctic Ocean, lat. 58° 85′ S., long. 108° 38′ E. Magnified 300 diameters.

Bilin, Bohemia; Aberdeenshire.) It is on the sea-floor, however, that the most widespread deposits of diatom-ooze are to be found. *Diatomaceæ* occur in abundance, both in the surface-waters of the ocean and on the bottom. In the Arctic Ocean and in the seas around the Shetland Islands living diatoms sometimes form vast floating banks of a yellowish slimy mass, which impedes the prosecution of the herring fishery.[3] The frustules of these plants accumulate at depths of from 1260 to 1975 fathoms, as a pale straw-coloured deposit, which when dried is white and very light (Fig. 185). Messrs. Murray and Irvine estimate the area of sea-bottom covered with diatom ooze at 10,420,600 square miles, and the mean depth of the surface of the deposit at 1477 fathoms below sea-level.[4] Diatoms have contributed a not inconsiderable part of the material of

[1] W. H. Weed, *Botanical Gazette*, xiv. (1889), p. 117.

[2] W. H. Weed, *Amer. Journ. Sci.* xxxvii. (1889), p. 359. The action of *Hypnum aduncum* is adduced as an illustration of the less frequent precipitation of silica and the production of siliceous sinter by mosses.

[3] Sir J. Murray and Mr. Irvine, *Proc. Roy. Soc. Edin.* xviii. (1891), p. 231. On the source whence marine plants and animals obtain their silica, see *ante*, p. 575, and *postea*, p. 625.

[4] *Proc. Roy. Soc. Edin.* xvii. (1889), p. 82. For a detailed account of diatom-ooze, see the volume of the *Challenger Report* on "Deep-Sea Deposits," pp. 208-213.

various sinters and earths (*tuffeaux*) in the Tertiary and Cretaceous formations of Europe.[1]

6. Chemical Deposits formed by Plants.—Besides giving rise to new formations by the mere accumulation of their remains, plants do so also both directly and indirectly by causing precipitation from chemical solutions. This action has already been noticed as exemplified by the calcareous accumulations formed by nullipores and fresh-water algæ, and by the siliceous sinters and diatom-earths. But some further details concerning the general chemical results of the co-operation of vegetation may be given here. A conspicuous precipitation from calcareous springs known as calc-sinter was formerly thought to be merely an inorganic precipitate of lime. But it is now known to be immediately caused by the action of different aquatic plants. While the *Chara* deposits the carbonate within its own cells, the mosses *Hypnum*, *Bryum*, &c., precipitate the mineral as an inorganic incrustation outside their stems.[2]

Some observers have even maintained that this is the normal mode of production of calc-sinter in large masses like those of Tivoli.[3] It is certainly remarkable that this substance may be observed encrusting fibrous bunches of moss (*Hypnum*, &c.), when it can be found in no other part of the water-course, and this, too, at a spring containing only 0·034 of carbonate. It is evident that if the deposit of calc-sinter were due to mere evaporation, it would be more or less equally spread along the edges and shallow parts of the channel. It appears to arise first from the decomposition of dissolved carbonic acid by the living plants, and it proceeds along their growing stems and fibres. Subsequently, evaporation and loss of carbon-dioxide cause the carbonate to be precipitated over and through the fibrous sinter, till the substance may become a solid crystalline stone. Varieties of sinter are traceable to original differences in the plants precipitating it. Thus at Weissenbrunnen, near Schalkau, in Central Germany, a cavernous but compact sinter is made by *Hypnum molluscum*, while a loose porous kind gathers upon *Didymodon capillaceus*.[4]

Besides calcium-carbonate, vegetable life has the power of causing the precipitation of silica. The most signal examples of this operation are furnished at some hot springs where, as above remarked with regard to the geyser district of the Yellowstone Park, extensive sinter deposits are largely formed by vegetation, which causes the siliceous material to be thrown down as a stiff gelatinous substance, in many varied forms. Algæ are chiefly concerned in this process. On the death of the plant the jelly-like mass, which consists of the siliceous filaments of the algæ and their slimy envelope, loses part of its water, becomes cheese-like in consistency, and finally hardens into stone.[5]

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[1] L. Cayeux, *Ann. Soc. Géol. Nord*, xix. (1891), p. 90; *Compt. rend.* cxiv. (1892), p. 375; and his important monograph already cited, 'Contribution à l'Étude des Terrains sédimentaires,' especially chap. iii.

[2] Mr. Davis observes that this precipitation is noticeable on the leaves and stems of the higher plants, and that nearly all vegetation growing in water is concerned in producing it. *Journ. Geol.* viii. p. 485.

[3] On the influence of algæ in the formation of the travertine of Tivoli, see F. Cohn, *Neues Jahrb.* 1864, p. 580; G. vom Rath, *Z. D. G. G.* xviii. (1866), p. 502.

[4] See V. Schauroth, *Z. D. G. G.* iii. (1851), p. 137. Cohn, in the paper just cited, gives some interesting information as to the plants by which the sinter is formed, and their work. In Scotland, *Hypnum commutatum* is a leading sinter-former.

[5] W. H. Weed, *9th Ann. Rep. U. S. G. S.* 1889. *Amer. Journ. Sci.* xxxviii. (1889), p. 351.

The humus acids (p. 598), which possess the power of dissolving silica, precipitate it in incrustations and concretions. Julien describes hyalite crusts at the Palisades of the Hudson, due, as he thinks, to the action of the rich humus upon the fallen débris of diabase. The frequent occurrence of nodules of flint and chert in association with organic remains, the common silicification of fossil wood, and other similar close relations between silica and organic remains, point to the action of organic acids in the precipitation of this mineral. This action may consist sometimes in the neutralisation, by organic acids, of alkaline solutions charged with silica, sometimes in the solution and re-deposit of colloid silica by albuminoid compounds, developed during the decomposition of organic matter in deposits through which silica has been disseminated, the deposit taking place preferentially round some decaying organism, or in the hollow left by its removal.[1]

Again, in the formation of extensive beds of bog-iron-ore, the agency of vegetable life is of prime importance. In marshy flats and shallow lakes, where the organic acids are abundantly supplied by decomposing plants, the salts of iron are attacked and dissolved. Exposure to the air leads to the oxidation of these solutions, and the consequent precipitation of the iron in the form of hydrated ferric oxide, which, mixed with similar combinations of manganese, and also with silica, phosphoric acid, lime, alumina and magnesia, constitutes the bog-ore so abundant on the lowlands of North Germany and other marshy tracts of northern Europe.[2] On the eastern sea-board of the United States, large tracts of salt-marsh, lying behind sand-dunes and bars, form receptacles for much active chemical solution and deposit. There, as in the European bog-iron districts, ferruginous sands and rocks containing iron are bleached by the solvent action of humus acids, and the iron removed in solution is chiefly oxidised and thrown down on the bottom. In presence of the sulphates of sea-water and of organic matter, the iron of ferruginous minerals is partially changed into sulphide, which on oxidation gives rise to the precipitation of bog-iron.[3] The existence of beds of iron-ore among sedimentary formations affords strong presumption of the existence of contemporaneous organic life by which the iron was dissolved and precipitated.

**Animals.**—Animal formations are chiefly composed of the remains of the lower grades of the animal kingdom, especially of *Mollusca*, *Actinozoa*, and *Foraminifera*.

1. Calcareous.—Lime, chiefly in the form of carbonate, is the mineral substance of which the solid parts of invertebrate animals are mainly built up. The proportion of carbonate of lime in sea-water is so

[1] Julien, *Proc. Amer. Assoc.* xxviii. (1879), p. 396; Sollas, *Ann. Mag. Nat. Hist.* Nov. Dec. 1880; J. Roth, 'Allgem. chem. Geologie,' p. 576; Dr. Von Ollech's pamphlet cited *ante*, p. 606; LeConte, *Amer. Journ. Sci.* 1880, p. 181.

[2] Forchhammer, *Neues Jahrb.* 1841, p. 17; *ante*, p. 581.

[3] Julien, *op. cit.* p. 347, and *ante*, p. 187. For a discussion of the conditions for the formation of the Swedish lake-ores, see H. Sjögren, *Geol. Fören. Stockholm*, xiii. (1891), p. 373.

small as to have presented a difficulty in the endeavour to account for the vast quantities of this substance eliminated by marine organisms. Mr. J. Y. Buchanan, however, has suggested that the testaceous denizens of the sea assimilate their lime from the gypsum dissolved in sea-water, forming sulphide in the interior of the animal, which is transformed into carbonate on the outside.[1] Messrs. Murray and Irvine have experimentally proved that sea-animals can secrete carbonate of lime from sea-water from which carbonate of lime is rigidly excluded, and thus that the other lime salts, notably the sulphate, are made use of in the process. They infer that the living tissues of the lower animals and the effete secretions of higher forms produce carbonate of ammonia, which in presence of the sulphate of lime of sea-water becomes carbonate of lime and sulphate of ammonia.[2] The great majority of the accumulations formed of animal remains are calcareous. Those organisms which secrete their lime as calcite produce more durable skeletons or tests than those which accumulate it in the form of aragonite (p. 155). Hence among geological formations aragonite shells have in large measure disappeared.[3]

In fresh water, accumulations of animal remains are represented by the white, chalky *marl* of lakes, which consists in large part of the mouldering remains of *Mollusca*, *Entomostraca* and *Chara* or other fresh-water algæ. On the sea-bottom, in shallow water, they consist of beds of shells, as in oyster-banks. Under favourable conditions, extensive deposits of limestone are now being formed on the sea-floor in tropical latitudes. Murray, from observations made during the *Challenger* voyage, estimates that in a square mile of the tropical ocean down to a depth of 100 fathoms there are more than 16 tons of calcareous matter in the form of animal and vegetable organisms.[4] These surface organisms, when dead, are continually falling to the bottom, where their remains accumulate as a soft ooze. On the floor of the West Indian seas, as originally described by Pourtalès, where an extraordinarily abundant fauna is supported by the plentiful supply of food brought by the great ocean currents which enter that region from the South Atlantic, a calcareous deposit is being formed out of the hard parts of the animals that live on the bottom (mollusks, echinoderms, corals, alcyonoids, annelids, crustacea, &c.), mingled with what may fall from the upper water. This deposit accumulates as a vast submarine plateau or series of broad banks, and is comparable in extent to some of the more important limestones of older geological time. Some portions of it have here and there (Barbados, Guadeloupe, Cuba, &c.) been elevated above the sea, so that its composition and structure can be studied. The organisms in these upraised

[1] *Brit. Assoc.* 1881, Sects. p. 584.

[2] *Proc. Roy. Soc. Edin.* xvii. (1889), p. 89.

[3] Sorby, Presidential Address Geol. Soc. 1879; P. F. Kendall, *Geol. Mag.* 1883, p. 497; V. Cornish and P. F. Kendall, *Geol. Mag.* 1888, p. 60. The last-named observer remarks that all reef-building corals have aragonite skeletons, while those of all the deep-sea forms which he had studied were of calcite (*Rep. Brit. Assoc.* 1896, p. 789). See *postea*, Book V. § ii. 2.

[4] *Proc. Roy. Soc. Edin.* x. (1880), p. 508.

limestones are the same as those which still live, and form a similar limestone in the surrounding seas. In Yucatan the rock is perforated with caverns, one of which is 70 fathoms deep.[1]

Here and there considerable deposits of broken shells have been produced by the accumulation of the excrement of fishes, as Verrill has pointed out, on the north-eastern coasts of the United States. Deposits of broken shells, raised above sea-level either by breakers and winds or by subterranean movements, are solidified into more or less compact shelly limestone. Extensive beds of this nature, composed mainly of species of *Arca*, *Lutraria*, *Mactra*, &c., form islands fronting the shores of Florida, and likewise underlie the soil of that State. Some of the shells still retain their colours. The whole mass is in layers 1 to 18 inches thick, quite soft before exposure to the air, but hardening thereafter, and much of it exhibiting a confused crystallisation.[2] It is known locally as Coquina. The calcareous dunes of Bermuda have been already referred to (p. 443).

*Coral-reefs.*[3]—But the most striking calcareous formations now in

[1] A. Agassiz, *Amer. Acad.* xi. (1882), p. 111; and 'Three Cruises of the *Blake*.' See also papers by Messrs. Jukes-Browne and Harrison, *Q. J. G. S.* xlvii. (1891), p. 197; xlviii. (1892), p. 170; lv. (1899), p. 177, on the oceanic deposits of Barbados and Trinidad; and for the general subject, Sir J. Murray on "Marine Organisms and their Environment," *Nature*, lv. (1897), p. 227.

[2] H. D. Rogers, *Brit. Assoc. Rep.* 1834, p. 11.

[3] The literature devoted to the structure and origin of Coral-reefs has grown to large proportions in recent years. The following list includes the more important contributions to the subject:—Darwin, 'The Structure and Distribution of Coral Islands,' 1842; 2nd edit. 1874; 3rd edit. by Professor Bonney, 1889; Dana, 'Corals and Coral Islands,' 1872; 2nd edit. 1890; Jukes's 'Narrative of Voyage of H.M.S. *Fly*,' 1847; C. Semper, *Zeitsch. Wissen. Zool.* xiii. (1863), p. 558; *Verhandl. Phys. Med. Gesellsch.*, Würzburg, Feb. 1868; 'Die Philippinen und ihre Bewöhner,' 1869, p. 100; J. J. Rein, *Senckenb. Naturf. Ges.*, Würzburg, 1869-70, p. 157; J. Murray, *Proc. Roy. Soc. Edin.* x. p. 505, xvii. (1889), p. 79; A. Agassiz, *Mem. Amer. Acad.* xi. (1882), p. 107; (Hawaii) *Bull. Mus. Compar. Zool. Harvard*, xvii. (1889), p. 121; xx. (1890), p. 61; xxiii. (1892), p. 1; (Bahamas and Cuba) xxvi. (1894), pp. 1-203; (Bermudas) xxvi. (1895), p. 209; (Australian Barrier-reef) xxviii. (1898), p. 95; (Fiji) xxxiii. (1899), pp. 3-167; *Amer. Jour. Sci.* ii. (1896), p. 240; v. (1898), p. 113; xiii. (1902), p. 297; *Mem. Mus. Comp. Zool. Harvard*, xxvi. (1902), pp. 1-113 ("Preliminary Report of *Albatross* Expedition across Tropical Pacific"); C. P. Sluiter, on the coral-reefs of the Java Sea, *Natuurkund. Tijd. Nederlandsch. Indië*, xlix. (1890); J. Walther, on the coral-reefs of the Sinai peninsula, *Abhand. Math.-Phys. Kön. Sachs. Gesell.* xiv. (1888); H. B. Guppy, *Proc. Linn. Soc. N. S. Wales*, ix. part 4; *Trans. Roy. Soc. Edin.* xxxii. (1885); 'The Solomon Islands,' 1887; J. C. Bourne, *Nature*, xxxvii. (1888), pp. 415, 546; Admiral Wharton, *ibid.* pp. 303, 393; xxxviii. (1888), pp. 207, 568; xlii. (1890), pp. 81, 85, 172, 222; lv. (1897), p. 390; *Q. J. G. S.* lv. (1898), p. 228; A. Heilprin, 'The Bermuda Islands,' 1889; *Proc. Acad. Nat. Sci. Philadelphia*, 1890, p. 303; Jukes-Browne and Harrison, Barbados, *Q. J. G. S.* xlvii. (1891), p. 197; xlviii. (1892), p. 170; Walther, *Peterm. Mitth.* Ergänz. No. 102 (1891); J. J. Lister (Tonga Island), *Q. J. G. S.* xlvii. (1891), p. 590; W. Savile Kent, 'The Great Barrier-reef of Australia,' London, 1893 (pp. 387, 64 plates); G. Gerland, "Die Koralleninseln vornehmlich der Südsee," *Beiträge zur Geophys.* ii. (1894), pp. 25-70; A. Krämer, 'Ueber den Bau der Korallenriffe an den Samoanischen Küsten,' pp. ix, 174, Kiel and Leipzig. 1897; "The Atoll of Funafuti," published as *Memoir III.* of the Australian Museum, Sydney, 1896-98; J. S. Gardiner. *Proc. Cambridge Phil. Soc.* ix. (1898), p. 417; W. J. Sollas, *Nature*, lv. (1897), p. 137; "Funafuti: the Study of a Coral-atoll,"

progress are the reefs and islands of coral. These vast masses of rock are formed by the continuous growth of various genera and species of corals, in tracts where the mean temperature is not lower than 68° Fahr. Coral-growth is prevented by colder water, and by the fresh and muddy water discharged into the sea by large rivers. One of the essential conditions for the formation of coral-reefs is abundance of food for the reef-builders, and this seems to be best supplied by the great equatorial currents. It is observed that on the eastern coasts of Africa, Central America and Australia, bathed by ocean currents, extensive coral-reefs flourish; while on the western coasts, in corresponding latitudes, where no such powerful currents flow, only isolated patches of coral exist.[1]

Darwin and Dana concluded that reef-building corals cannot live at depths of more than about fifteen or twenty fathoms; they appear, indeed, not to thrive below a depth of six or seven fathoms. They cannot survive exposure to sun and air, and consequently are unable to grow above the level of the lowest tides. They are likewise prevented from growing by the presence of much mud in the water. Various observations and estimates have been made of the rate of growth of coral. Individual specimens of *Mæandrina* have been found to increase from half an inch to an inch in a year, and others of *Madrepora* have grown three inches in the same time.[2] Specimens of *Orbicella*, *Manicina* and *Isophyllia*, taken from the submarine telegraph-cable between Havana and Key West, showed a growth of from one to two and a half inches in about seven years. A. Agassiz estimates that in the Florida reef the corals could build up a reef from a depth of seven fathoms to the surface in 1000 or 1200 years.[3] When coral-reefs begin to grow, either fronting a coast-line or a submarine bank, they continue to advance outward, the living portion being on the outside, while on the inside the mass consists of dying or dead coral, which becomes a solid white compact limestone. In the coral area of the Pacific there are, according to Dana, 290 coral-islands, besides extensive reefs round other islands. The Indian Ocean contains some groups of large coral-islands; others occur in the Red Sea. Reefs of coral occur less abundantly in the tropical parts of the Atlantic, among the West Indian Islands and on the Florida coast, but they are absent from the Pacific side of Central America—a fact attributed by Professor Agassiz not to a cold marine current, as suggested by Professor Dana, but to the enormous amount of mud poured into the sea

*Natural Science*, Jan. 1899, p. 17; Professor Bonney, *Nature*, lvii. p. 187; *op. cit.* lix. (1898), pp. 22, 29; Mrs. Edgeworth David, 'Funafuti, or, Three Months on a Coral-island,' London, 1899; E. C. Andrews on "The Limestones of the Fiji Islands," *Bull. Mus. Comp. Zool. Harvard*, xxxviii. (1900), p. 1; R. T. Hill, "The Geology of Jamaica," *op. cit.* xxxiv. (1899), pp. 1-256; C. W. Andrews, 'Christmas Island,' 1900, pp. xiii. 337 (published by Trustees of Brit. Museum); Hume, *Compt. rend. Congrès Géol. Internat. Paris*, 1900, p. 923 (Red Sea); J. W. Spencer, *Q. J. G. S.* lvii. (1901), p. 490 (West Indies).

[1] A. Agassiz, *Amer. Acad.* xi. (1882), p. 120.

[2] Dana, 'Corals and Coral Islands,' 2nd edit. 1890, p. 123.

[3] *Amer. Acad.* xi. (1882), p. 129. See also *Bull. Mus. Comp. Zool. Harvard*, xx. (1890), p. 61.

on this side during the rainy season.[1] The great reef of Australia is 1250 miles long and from 10 to 90 miles broad.[2]

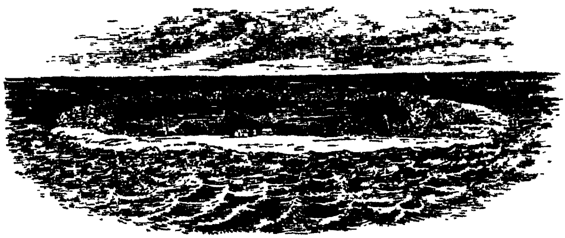


Fig 186 – View of an Atoll or Coral-island.

Coral-rock is not entirely formed by the continuous growth of the

Fig. 187.—Chart of Keeling Atoll, Indian Ocean (after Darwin).
The white portion represents the reef above sea-level, the inner shaded space the lagoon, of which the deepest portion is marked by the darker tint.

polyps. It is largely composed of calcareous foraminifera, which are

[1] *Bull. Mus. Comp. Zool.* xxiii. (1892), p. 70.

[2] See the memoir by A. Agassiz, and the volume of W. Saville-Kent, cited on p. 614, and a paper by H. O. Forbes, *Geograph. Journ.* ii. (1893), p. 540.

washed in among the living and dead coral.[1] It gradually loses any distinct organic structure, and acquires an internal crystalline character like an ancient limestone, owing to the infiltration of water through its mass, whereby calcium-carbonate is carried down and deposited in the pores and crevices, as in a growing stalactite (p. 178). Great quantities of calcareous sand and mud are produced by the breakers which beat upon the outer edge of the reefs. This detritus is partly washed up upon the reefs, where, being cemented by solution and re-deposit, it aids in their consolidation, sometimes acquiring an oolitic structure;[2] but much of it is swept away by the ocean currents and distributed over the sea-floor, the water becoming milky with it after a storm.[3] Around volcanic islands much lava-detritus may be mixed with the coral-sand and mud. Thus at Hawaii, where great abrasion by the waves takes place on the ends of the lava-streams which have run out to sea, large quantities of olivine sand are formed, the grains of this mineral varying from the size of a bean or pea downwards to the finest particles. This sand becomes mixed with the coral detritus, and is also interstratified with it in layers.[4]

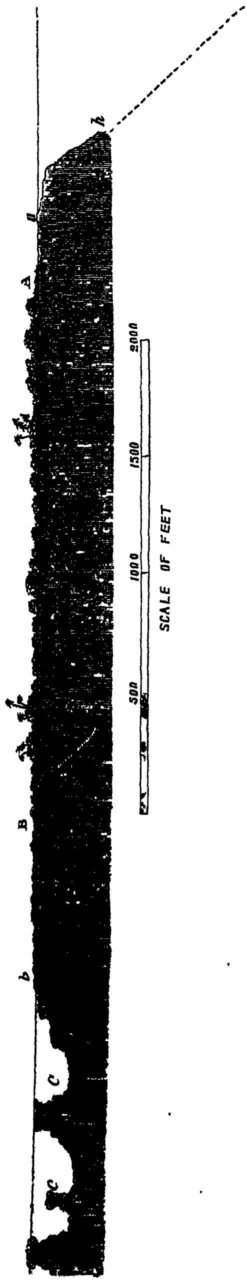



Fig. 188.—Section of a Coral-reef.
A B, portion above tide-mark (*a b*), covered with vegetation and habitable; C C, edge of lagoon, with insular masses of coral (D D); the open ocean lies to the right of the slope *a h*.

[1] Guppy, 'Solomon Islands,' p. 73; *Trans. Roy. Soc. Edin.* xxxii. (1885), pp. 545-581; Lister, *Q. J. G. S.* xlvii. (1891), p. 602.

[2] See Dana's 'Corals and Coral Islands,' pp. 152, 194; A. Agassiz, *Mem. Amer. Acad.* xi. (1882), p. 128.

[3] A. Agassiz mentions that after a storm the sea is sometimes discoloured by this silt to a distance of six to ten miles from the outer reef, and he adds that he has seen between two and three inches of fine silt deposited in the interval between two tides after a prolonged storm: *Amer. Acad.* xi. p. 126. The total area of sea-floor covered with coral sand and mud is estimated by Messrs. Murray and Irvine at 3,219,800 square miles. *Proc. Roy. Soc. Edin.* xvii. (1889), p. 82.

[4] W. L. Green, *Journ. Roy. Geol. Soc. Ireland*, iv. (1887), p. 140. This author suggestively points out the resemblance of such a mingling of calcareous material and magnesian silicate to the mingled limestones, serpentines and ophicalcites of the crystalline schists. Sollas, *Proc. Royal Dublin Soc.* (1891), p. 124.

As already mentioned (p. 390), the formation of coral-islands has been explained by Darwin on the hypothesis of a subsidence of the sea-floor. The circular islands, or atolls, rising in mid-ocean, have the general aspect shown in Fig. 186. Their external form may be understood from the chart (Fig. 187), and their structure and the character of their surface from the section (Fig. 188). They rise with sometimes tolerably steep slopes from profound depths, until they reach the surface of the sea. But as the coral polyps do not live at a greater depth than about 15 or 20 fathoms, and could not have grown upward therefore from the bottom of a deep sea, Darwin inferred that the sites of these coral-reefs had undergone a progressive subsidence, the rate of their upward growth keeping pace, on the whole, with that of their depression. On this view, what is termed a *Fringing Reef* (A B, Fig. 189) would first be formed fronting the land (L) between the limit of the 20-fathom line and the sea-level (S S). Growing upward until it reached the surface of the water, it would be exposed to the dash of the waves, which would

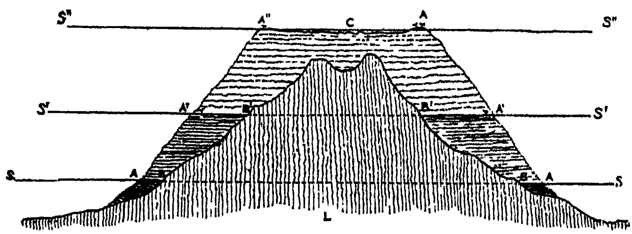



Fig. 189.—Diagram illustrating Darwin's theory of the formation of Atolls.

break off pieces of the coral and heap them upon the reef. In this way islets would be formed upon it, which, by successive accumulations of materials thrown up by the breakers or brought by winds, would remain permanently above water. On these islets, palms and other plants, whose seeds might be drifted from distant or adjoining land, would take root and flourish. Inside the reef, there would be a shallow channel of water, communicating, through gaps in the reef, with the main ocean outside. Fringing reefs of this character are of common occurrence at the present time. In the case of a continent, they front its coast for a long distance, but they may entirely surround an island.

If, according to the Darwinian explanation, the site of a fringing reef undergoes depression at a rate sufficiently slow to allow the corals to keep pace with it, the reef may be conceived to grow upward as fast as the bottom sinks downward. As the reef grows mainly on its seaward edge, the lagoon channel inside will become deeper and wider, while, at the same time, the depth of water outside will increase until a *Barrier Reef* (A′ B′, Fig. 189) is formed. In Fig. 190, for example, the Gambier Islands (1248 feet high) are shown to be entirely surrounded by an interrupted barrier reef, inside of which lies the lagoon. Prolonged slow depression would continually diminish the area of the land thus encircled, while the reef might retain much the same size and position. At last the

final peak of the original island might disappear under the lagoon (C, Fig. 189), and an *Atoll*, or true coral-island, would be formed (A″ A″, and Figs. 186 and 187). Should any more rapid or sudden downward movement take place, it might carry the atoll down beneath the surface, like the Great Chagos bank in the Indian Ocean, which is a submarine atoll.

This simple and luminous explanation of the history of coral-reefs accorded well with all the known facts, and led up to the impressive

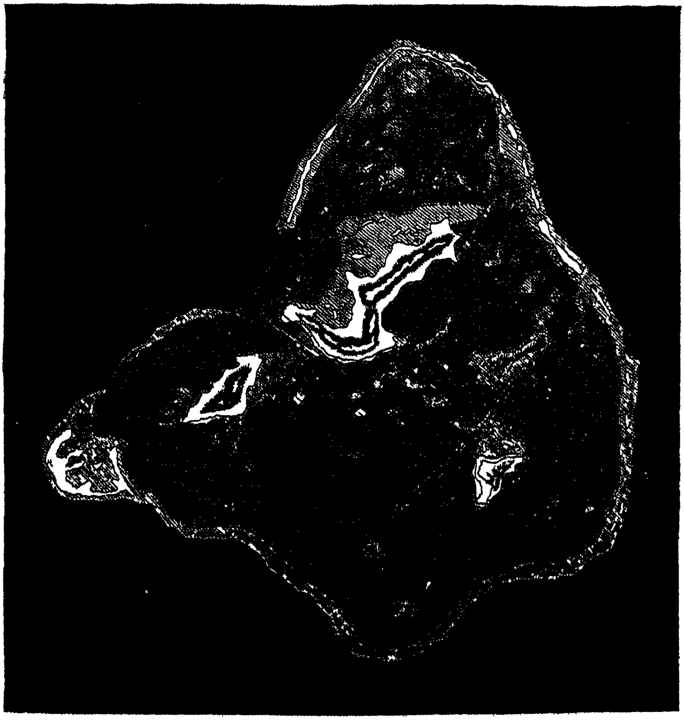


Fig. 190.—Chart of Gambier Islands, Pacific Ocean (after Beechy).

conclusion that a vast area of the Pacific Ocean, fully 6000 geographical miles from east to west, has undergone a recent subsidence, and may be slowly sinking still.

Mr. Darwin's views having been generally accepted by geologists, coral-islands have been regarded with special interest as furnishing proof of vast oceanic subsidence. In the year 1868, C. Semper pointed to some cases of atolls which, he said, could not be explained by Darwin's theory. The Pelew Islands, at the western end of the Caroline archipelago, show true atolls at their northern extremity, while at their southern end, only 60 miles away, there are raised coral-reefs, and an island entirely destitute of reefs. Semper considered that the atolls had grown up under the influence of peculiar conditions of marine

currents and erosion, simultaneously with elevation rather than subsidence.[1] In 1870, J. J. Rein cited the case of Bermuda as one capable of explanation by upgrowth of calcareous accumulations from the bottom without subsidence.[2] Subsequently, Sir John Murray, whose researches in the *Challenger* Expedition led him to make detailed examination of many coral-reefs, remarked that barrier-reefs do not necessarily prove subsidence, seeing that they may grow outward from the land

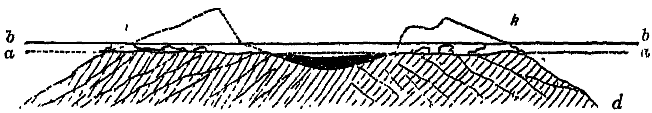



Fig. 191.—Section of a Volcanic Cone of loose ashes supposed to have been thrown up on the sea-floor and to have reached the sea-level (*B.*).

upon the top of a talus of their own débris broken down by the waves, and may thus appear to consist of solid coral which had grown upward from the bottom during depression, although only the upper layer, 20 fathoms or thereabouts in thickness, is composed of solid, unbroken coral growth. He pointed out that in the coral-seas the islands appear to have always started on volcanic ejections, at least that all the non-calcareous rock now visible is of volcanic origin. Where the submarine peak lay

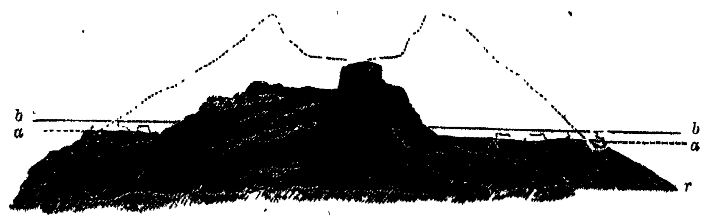



Fig. 192.—Section of denuded Volcanic Island with lava nucleus and surrounding coral-reef (*B.*).

below the inferior limit of coral growth, it may have been brought up to the requisite level by the gradual accumulation of the remains of organisms.[3] Where the original eminence rose above the sea, the projecting portion (Fig. 191) may be supposed to have been cut down to the lower limit of breaker-action (*a a*), so as to offer a platform on which corals might build reefs (*i k*) up to the level of high-water (*b b*). Or with less denudation, or a loftier or more durable cone, a nucleus of the original volcano might remain as an island (Fig. 192), from the sides of which a barrier reef might grow outward, on a talus of its own débris (*r r*), and maintain a steep outer slope. According

[1] See Semper's papers quoted in footnote on p. 614. In the Appendix to the second edition of his 'Coral Reefs' (p. 223) Mr. Darwin replied to Semper's criticism, maintaining that his objections present no insuperable difficulty in the theory of subsidence.

[2] See paper cited in footnote on p. 614.

[3] "A submarine peak," says Professor A. Agassiz, "is built up by the carcases of the invertebrates that live upon it, and for which the pelagic fauna serves in part as food." *Bull. Mus. Comp. Zool. Harvard*, xvii. No. 3 (1889), p. 137.

to this view the breadth of a reef ought, in some degree, to be a measure of its antiquity.

To the obvious objection that this explanation requires the existence of so many volcanic peaks just at the proper depth for coral-growth, and that the number of true atolls is so great, Sir John Murray replies that in several ways the limit for the commencement of coral-growth may be reached. Volcanic islands may be reduced by the waves to mere shoals (Fig. 191), like Graham's Island, in the Mediterranean, and the recent volcanic islands in the Tonga group above described (p. 334).[1] On the other hand, submarine volcanic peaks, if originally too low, may conceivably be brought up to the coral-zone by the constant deposit of the detritus of marine life (foraminifera, radiolaria, pteropods, &c.), which, as above stated, is found to be very abundant in the upper waters, whence it descends as a kind of organic rain into the depths. Sir John Murray holds also that the dead coral, attacked by the solvent action of the sea-water, is removed in solution both from the lagoon (which may thus be deepened) and from the dead part of the outer face of the reef, which may in this way acquire greater steepness.[2]

Professor A. Agassiz has arrived at similar conclusions from an extensive series of detailed explorations among the coral-reefs and submarine banks of the West Indian seas and the Pacific Ocean, and the Great Barrier-reef of Australia.[3] He believes that barrier-reefs and atolls have arisen without the aid of subsidence, upon a platform prepared for them by the upward growth of submarine calcareous banks, under the most favourable condition of ocean-currents, temperature, and food.

Observations have now multiplied which prove that in many places where atolls exist there has unquestionably been a movement of upheaval. Corroborating the original deductions of Semper and Rein, Professor Agassiz has shown that in the Pacific Ocean upheaval has extended over the whole of the Fiji group, where it has exceeded 1000 feet in amount, and has uplifted a mass of Tertiary coralliferous limestone, which in the Tonga islands forms a cliff more than 1000 feet high. He has observed that the islands, where not volcanic, are mainly made up of this limestone, which must at one time have had a wide extent, and that in the Tonga, Society and Cook groups the recent corals have played no part in the formation of the land, but form a mere thin crust or shell on platforms which have been levelled for them by the sea, either in the Tertiary limestone, or in volcanic rocks.[4] He has noted abundant terraces marking former shore-lines at successive elevations. On the island of Niue (or Savage Island), to the east of the Tonga group, three such terraces occur at heights of 5 to 10, 50 to 60, and 90 to 100 feet, while far to the north, on the island of Rota, at the

[1] Sir W. J. Wharton (*Nature*, lv. 1897, p. 390) believes that the sea can cut down a volcanic cone to below 20 fathoms, and that in this way volcanic peaks which reached sea-level may be reduced to the depth required for coral-growth. For examples of the rapid levelling down of new volcanic cones by the waves and the reduction of an island to a sunken reef, see *ante*, p. 333 *et seq.*

[2] *Proc. Roy. Soc. Edin.* 1880, p. 505, *ante*, p. 566. As already stated, Professor Agassiz also attributes great importance to this solvent power of the sea in lowering the level of dead coral-reefs and limestones. *Bull. Mus. Comp. Zool.* xxviii. (1896), p. 39.

[3] See the list of his contributions to the subject cited on p. 614.

[4] *Mem. Mus. Comp. Zool. Harvard*, xxvi. (1902), p. 34.

southern end of the Ladrones, no fewer than seven may be counted.[1] Professor Agassiz shows that atolls do not always rise from profound depths, but, as in the case of the Fiji group, may be formed on the top of eminences rising from a submarine platform, which may not be more than 800 fathoms beneath sea-level.[2] He has found likewise proofs of elevation along the coast of Queensland fronting the Barrier-reef, where for a distance of more than 1000 miles the uprise is said to exceed 2500 feet. In the New Hebrides upraised coral-reefs have been met with at 1500 feet above sea-level.[3] As already stated (p. 382), evidence of elevation of coral-reefs has likewise been collected from the Solomon Islands[4] and from Southern Japan. It would thus appear that widespread traces of upheaval have been met with all over the Pacific basin, which has been claimed as especially a region of subsidence.

Similar testimony has been gathered in the western part of the Atlantic basin, with its connected enclosed seas. Thus the whole of the West Indian region, except the leeward side of the Windward Islands, displays on its numerous coral-fringed islands a succession of terraces which mark an interrupted and unequal elevation of the sea-bottom. In Barbados the uplift has amounted to nearly 1100 feet. Near the Windward Passage it is at least 600 feet, and it diminishes thence towards the north, south and west, being only a few feet at Colon, and in Southern Florida.[5]

Again, in the Indian Ocean and the Red Sea, proofs of the elevation of coral-reefs present themselves. The most striking example yet recorded from this region is that of Christmas Island, which appears to be a volcanic cone 15,500 feet high, of which the upper 1100 feet rise above the level of the sea. The volcanic pile has been covered with a mass of Tertiary limestone, in which the latest lavas and tuffs of the submarine volcano are intercalated. The summit of the island is covered with reef deposits, and is believed to have been an atoll.[6]

From this accumulation of evidence, it must now, I think, be conceded that the widespread oceanic subsidence demanded by Darwin's theory cannot be demonstrated by coral-reefs. The co-existence of fringing and barrier-reefs, and of atolls, in the same neighbourhood with proofs of protracted stability of level or with evidence of actual and considerable upheaval, likewise the successive stages whereby a true atoll may be formed without subsidence, have in some cases been demonstrated so clearly that we must admit the possibility that the same mode of formation may extend all over the coral-seas. At the same time, it may be granted that the necessary conditions for the formation of barrier-reefs and atolls might sometimes be brought about by subsidence. So long as a suitable bottom is provided for coral-growth it is probably immaterial whether this is done by the submergence of land or by the ascent of the sea-floor. That subsidence has in some cases taken place may be indicated by the depth of some atoll-lagoons—40 fathoms,—unless this depth can be supposed to be due to solution by sea-water, and not to the progressive deepening during a subsidence with which the upward growth of the reef could keep pace.

[1] *Op. cit.* p. 42. [2] *Op. cit.* pp. 20, 21.

[3] G. C. Frederick, *Q. J. G. S.* xlix. (1893), p. 227.

[4] See works of Dr. Guppy, cited on pp. 382, 614.

[5] A. Agassiz, *Bull. Mus. Comp. Zool. Harvard*, xxvi. (1894), pp. 108-166; Hill, *op. cit.* xxxiv. p. 219; Jukes-Browne and Harrison, *Q. J. G. S.* xlvii. p. 209.

[6] C. W. Andrews, 'A Monograph of Christmas Island, Indian Ocean,' published by the British Museum, 1900; and *ante*, p. 338.

Obviously, if the doctrine of subsidence, as taught by Darwin, were true, it would imply the accumulation of enormously thick coral formations over the vast areas of the ocean-basins. It was long ago objected to this doctrine by one of the shrewdest geologists of last century that its acceptance implied the existence of such formations at least 2000 or 3000 feet thick; that if such masses are forming now, they may be presumed to have been produced also in earlier geological times, but that nowhere on the land which represented a former sea-bottom had any bed or formation of coral even 500 feet thick been discovered.[1] Lyell, in answering this criticism, remarked that while it was premature to assert that there are no recent coral formations uplifted to great heights, there exist in the Alps and Pyrenees masses of "Cretaceous and Oolitic limestones, 3000 or 4000 feet thick, in great part made up of coralline and shelly matter, which may present us with a true geological counterpart of the recent coral-reefs of equatorial seas."[2] But observations have multiplied in recent years, and Maclaren's acute objection has been sustained. It has been ascertained, where coral-reefs have been upraised for hundreds of feet above sea-level, that the whole of the calcareous mass is not coral rock, but consists mainly of a lower formation of calcareous detrital materials, on which the corals have begun to build, exactly as postulated by Messrs. Murray and Agassiz. This calcareous substratum may be recent or of Tertiary age. In Fiji, where it has been upraised to more than 1000 feet above the sea, it is probably Pliocene, or, in the lower parts, even older. As the modern coral-reefs have been built on a denuded surface of this older limestone, it is obvious that any boring through the modern reef in such islands must pass through a great thickness of limestone, in which a few corals may occur, before it reaches the underlying volcanic summits. Hence, as Professor Agassiz has pointed out, the recent boring at Funafuti will not really solve the problem of atoll-formation. Nowhere have the sheets of upraised coral-reefs been found to be more than 200 to 250 feet thick, which may be assumed to be the maximum thickness of the reefs that are now growing. On the Florida "Keys," where a recent coral-reef has been elevated from 2 to 8 feet above sea-level, the total thickness of coral formed since Pliocene time has only been about 50 feet. The reef is based on Tertiary limestone. Re-examination of the limestones of the Eastern Alps, which were regarded as true coral-reefs, upwards of 2000 feet thick, has proved them to be of detrital origin, the true reefs being not more than 150 feet thick.[3]

*Ooze.*—The bed of the Atlantic and other oceans is covered with a

[1] Charles Maclaren, *Edin. New Phil. Journ.* 1843.

[2] 'Principles,' edit. 1886, ii. p. 606.

[3] Agassiz, *Bull. Mus. Comp. Zool. Harvard*, xxvi. p. 179; xxviii. (1896), p. 31; *Amer. Journ. Sci.* vi. (1898), p. 165. Rothpletz, 'Ein geologischer Querschnitt durch die Ost-Alpen,' Stuttgart, 1894, part i. pp. 52-68. Miss Ogilvie (*Geol. Mag.* 1894, pp. 1, 49), in describing the coral-banks among the limestones of the Southern Tyrol, has stated that, in so far as they bear on theories of coral-reefs, they lend support to the more modern view rather than to that of Darwin.

calcareous ooze formed of the remains of *Foraminifera*, chiefly species of the genus *Globigerina*. It has been observed that in these deep-sea deposits, the larger and relatively thinner pelagic shells are rare or absent at greater depths than 2000 fathoms, while the thicker-shelled varieties abound. This has been referred to the solvent action of sea-water, whereby the more fragile forms are attacked and removed in solution (*ante*, pp. 566, 621). These organisms do not live in the deeper water, but in the upper layers, whence their dead forms fall as a constant rain of calcareous matter to the bottom. Among abysmal deposits, foraminiferal ooze ranks next in abundance to the red and grey clays of the deep sea (p. 583). It is a pale-grey marl, sometimes red from peroxide of iron, or brown from peroxide of manganese; and it usually contains more or less clay, even with occasional fragments of pumice. It covers an area of the North Atlantic probably not less than 1300 miles from east to west, by several hundred miles from north to south. The total area of ocean-bottom occupied by globigerina-ooze is estimated at 47,752,500 square miles, the mean depth of the surface of the deposit below sea-level is computed to be 1996 fathoms, and the mean proportion of carbonate of lime in the ooze 64·53 per cent.[1]

The consolidation of a soft calcareous ooze or a mass of broken shells, corals and other calcareous organisms, effected by the percolation of water containing carbonic acid (*ante*, pp. 178, 617), is most rapid with copious evaporation, as, for instance, on coral-reefs where exposure to the air in the interval between two tides suffices for the deposit of a thin crust of hard limestone over a surface of broken coral or coral-sand.[2] Recently upraised limestone and coral-rock have in some places assumed a crystalline structure by this process, and the more delicate organisms have disappeared from them. But the calcareous deposits may acquire, even under the sea, sufficient cohesion to be capable of being broken up into blocks. On the submarine plateau off Florida, the trawl or dredge frequently brings up large fragments of the limestone now in course of formation on the bottom, consisting of the dead carcases of the very species that live upon the surface of the growing deposit.[3]

2. Siliceous.—Deposits formed from animal exuviæ are illustrated by another of the deep-sea formations brought to light by the *Challenger* researches. In certain regions of the western and middle Pacific Ocean, the bottom was found to be covered with an ooze consisting almost entirely of *Radiolaria*. These minute organisms occur, indeed, more or less abundantly in almost all deep oceanic deposits. From the deepest sounding taken by the *Challenger* (4475 fathoms, or more than 5 miles) a radiolarian ooze was obtained (Fig. 193). The spicules of sponges likewise furnish materials towards these siliceous accumulations. The number of marine plants and animals which secrete silica is so great, and the proportion of that constituent in sea-water so minute, that some

[1] Murray and Irvine, *Proc. Roy. Soc. Edin.* xvii. (1889), p. 82.

[2] A. Agassiz, *Amer. Acad.* xi. (1882), p. 128.

[3] A. Agassiz, *op. cit.* p. 112. Some of the upraised oceanic deposits of Barbados, according to Messrs. Jukes-Browne and Harrison (*Q. J. G. S.* xlviii. p. 170), present a close resemblance to those ascertained by dredging to be seen in progress of accumulation in deep parts of the ocean. For a comparison of globigerina-ooze with chalk, see L. Cayeux's work (cited on p. 166), chap. xiii.

difficulty has been felt to account satisfactorily for the vast quantities of silica continually being abstracted from the ocean by organic agencies. Messrs. Murray and Irvine, however, as already stated, have shown that an appreciable amount of fine clay is present even in the water of mid-ocean, and they have ascertained by actual experiments with living diatoms that these plants can obtain their silica from diffused clay in suspension.[1]

Fig. 198.—Radiolarian Ooze.
Dredged up by the *Challenger* Expedition, from a depth of 4475 fathoms, in lat. 11° 24′ N., long. 143° 10 E. Magnified 100 diameters. This is from the deepest abyss whence organisms have yet been dredged.

Abundant examples of siliceous strata (cherts, flints), formed by the aggregation of the remains of radiolaria or sponge-spicules, occur among the rocks of the earth's crust from the Cambrian system upward. They show that the process of silicification, already alluded to (*ante*, p. 179), comes into play in such deposits, which consist not merely of the siliceous organisms but of silica, which has been deposited among them, and has cemented them into an exceedingly compact stone.[2] In many cases silica has replaced the original carbonate of lime of the organisms, which are thus preserved as casts or pseudomorphs in flint or chert. This transformation has been demonstrated

[1] Murray and Irvine on siliceous deposits of modern seas, *Proc. Roy. Soc. Edin.* xviii. (1891), p. 229, and *ante*, p. 575.

[2] Examples of some of these ancient siliceous strata will be cited in Book VI. In illustration, reference may be made to a paper by Professor Sollas, *Ann. Mag. Nat. Hist.* 1880, pp. 384, 437; and a later paper, "A Contribution to the Natural History of Flints," *Proc. Roy. Dublin. Soc.* 1887; to three by Dr. Hinde, *Phil. Trans.* 1885, part ii. p. 403; *Geol. Mag.* 1887, p. 435; 1888, p. 241; to one on rhythmically thin-bedded radiolarian cherts in California, by Messrs. A. C. Lawson and C. Palache, *Bull. Geol. Univ. California*, vol. ii. No. 12 (1892), pp. 349-450; and to the discussion of the subject by M. Cayeux in chaps. i.-iii. of his work cited on p. 106.

artificially by Professor Church, who in a dilute solution of colloid silica converted a coral into silica.[1] There can be no doubt that on the floor of the Cambrian, Carboniferous and Cretaceous seas this transformation went on abundantly, the carbonate of lime being slowly dissolved and replaced by silica, sometimes in such detailed perfection that the original minute structures of the organisms have been well preserved. It must be admitted, however, that no modern flints, either complete or in course of formation, have yet been dredged up from the bed of the sea at the present day.

3. Phosphatic.—Deposits of this nature, in the great majority of cases, betoken some of the vertebrate animals, seeing that phosphate of lime enters largely into the composition of their bones, and occurs in their excrement (p. 180). The most familiar modern accumulations of this nature are the guano-beds of rainless islands off the western coasts of South America and Southern Africa. In these regions, immense flocks of sea-fowl have, in the course of centuries, covered the ground with an accumulation of their droppings to a depth of sometimes 30 to 80 feet, or even more. This deposit, consisting chiefly of organic matter and ammoniacal salts, with about 58 per cent of phosphate of lime, has acquired a high value as a manure, and is being rapidly cleared off. It could only have been preserved in a rainless or almost rainless climate. In the west of Europe, isolated stacks and rocky islands in the sea are often seen to be white from the droppings of clouds of sea-birds; but it is merely a thin crust, which is not allowed to grow thicker in a climate where rains are frequent and heavy.

It has been discovered that the prolonged existence of guano upon trachyte gives rise to a remarkable alteration, wherein the silicic acid is gradually replaced by phosphoric acid. The result is the formation of a hydrated phosphate of alumina and iron. In this process of phosphatisation, Mr. Teall, who traced its stages from specimens obtained from Clipperton Atoll, found that while the characteristic microscopic structure of the volcanic rock is preserved, and the phenocrysts of sanidine have remained comparatively little affected, the ground mass is replaced by isotropic secondary material, which in some cases has wholly or partially filled the places of the sanidines, forming a pseudomorph of trachyte.[2] The interstitial material of the rock is first attacked, then the microlitic felspars of the ground-mass, and last of all the porphyritic sanidines. A similar instance of phosphatisation has been found on the summit of Christmas Island in the Indian Ocean. Thick deposits of nearly pure phosphate of lime cap several of the higher hills, and doubtless represent the effects of percolation from the deposits of guano which accumulated on the low coral-islets close to sea-level before the atoll was uplifted. On one of the hills the rock consists largely of phosphates of alumina and iron, which may mark the position of a volcanic sheet, such as one of tuff, like those found on lower parts of the island.[3] Hydrated phosphate of alumina has likewise been found on the floor of a bone-cave in the valley of the Cesse in Hérault, under a deposit containing mammalian remains.[4] It is obvious, indeed, that wherever terrestrial mammalia congregate, and especially where they die and leave their carcases, phosphatic deposits may be formed if the conditions are favourable for the preservation of the remains. Caves haunted by hyænas serve as receptacles not only for the bones and excrement of these animals, but also for bones of the various animals which they

[1] *Journ. Chem. Soc.* xv. p. 107.

[2] J. J. H. Teall, *Q. J. G. S.* liv. (1898), p. 230.

[3] C. W. Andrews, 'Christmas Island,' pp. 271, 289.

[4] A. Gautier, *Compt. rend.* cxvi. (1893), p. 1491. Deposits in Redonda, West Indies, and at Connétable, an island off French Guiana, have probably had a similar origin.

have dragged there as food. Hence in limestone countries "osseous breccias" are often found below the layer of stalagmite on the floor. Again, along the swampy margins of lakes and salt-marshes the bodies of wild animals are often mired in the boggy ground and perish there, and their bodies gradually sink below the surface. Hence phosphatic accumulations arise sometimes on an extensive scale, as has happened in different parts of the United States.[1]

Phosphatic concretions, which are abundant on many horizons among the geological formations, have had their origin greatly elucidated by the deep-sea observations of recent years. It has been ascertained that phosphate of lime occurs in variable proportions among the deposits of the sea-floor. In the organic oozes it is always present, though the qnantity may be less than 1 per cent. It has been found in marked proportion among the deposits around continental shores, and is especially associated with glauconite in the green sands and blue muds. But it is likewise aggregated into irregularly shaped brownish concretions that vary from 1 to 3 centimetres in greatest diameter, and may exceptionally attain to from 4 to 6 centimetres. It has doubtless been directly derived from the remains of organisms, under the joint influence of organic matter and sea-water. Reduced to the condition of silt, and dissolved in the sea-water, it may be supposed to be endowed with the properties of colloidal bodies, such as hydrated silica, and to be ready to be precipitated round any fitting centre of accretion.[2] There can be little doubt that the phosphatic chalk of France, Belgium and England has had this origin. Grains and concretions of phosphate are found filling the interior of shells and foraminifera, or gathering round an organic nucleus, filling up its cavities, and in many cases replacing the original carbonate of lime.[3]

4. Glauconitic.—The occurrence of glauconite abundantly diffused through some deep-sea accumulations has been already referred to. It occurs in small, black, dark-green grains, which rarely if ever exceed 1 mm. in diameter, and likewise in particles of a pale-green colour, which distinctly bear the impress of the calcareous shells of foraminifera. Many of them are indeed merely internal casts of these organisms. Glauconite is thus frequently associated with calcareous organisms on the present sea-floor. It was obtained by the *Challenger* Expedition in greater or less abundance off the coast of Portugal, the west coast of Africa, the east coast of North America, the Cape of Good Hope, the Antarctic Continent, the coasts of Australia and New Zealand, the coasts of the Philippines, China and Japan, and the west coast of South America, while by other expeditions it has been observed in the Mediterranean, off the north coast of Scotland, the west coast of North America, the east coast of Africa and many other regions. Connected with the mineral detritus derived from the land, as might be expected from its geological distribution, it appears to be formed more especially in the cavities of calcareous

[1] See Penrose, *B. U. S. G. S.* No. 46 (1888), p. 127. C. W. Hayes, *17th Ann. Rep. U. S. G. S.* part ii., and *21st Rep.* part iii.

[2] Murray and Renard, "Deep-Sea Deposits," in *Challenger Reports*, pp. 391-398.

[3] A. Renard, J. Cornet and A. Strahan, in their memoirs already cited, *ante*, p. 181. See also Bleicher, *B. S. G. F.* 3rd ser. xx. (1892), p. 237.

organisms, where its initial stages of precipitation are influenced by the action of organic matter.[1] Glauconite in the typical granular form is widely distributed among the geological formations from the oldest Palæozoic to the most recent strata.

5. Deposits of Sulphides.—Reference has already been made (*ante*, p. 47) to the remarkable abundance of sulphuretted hydrogen in the deeper waters of the Black Sea, and to the connection of its appearance with the action of microbes. One of these organisms (*Bacterium hydrosulphuricum ponticum*) in the anærobic conditions of the deeper and denser portions of this great enclosed sea disengages the sulphuretted hydrogen, not only from decomposing organic matter, but also directly from the dissolved sulphates and sulphides. A portion only of the gas spreads through the waters, another part takes up iron and forms the abundant pyritous deposits that are found over the floor of the sea, while in the upper waters it is believed to be oxidised by another tribe of microbes or sulfo-bacteria.[2] The sulphide of iron is met with in the blue mud and other sediments of the bottom in the shape of minute globular grains sometimes aggregated into larger spherules or elongated irregular branching forms. The analogy of such deposits with the pyritous shales and clays of many old geological formations is of much interest and importance.

6. Earthy Deposits.—Besides the action of the common earth-worm in bringing up finely divided soil to the surface of the ground (pp. 460, 600), other animals furnish still more obtrusive examples of the transport of earthy materials. Among these the ants have long been familiar for the transformations which they produce on the surface of a district in which their colonies abound. They pile up mounds of fine earth, particles of stone and fragments of vegetation, which in temperate latitudes may vary from a few inches to several feet in height, but which in tropical countries, such as Brazil, reach a height of fourteen feet with a breadth of thirty feet across at the base.[3] Not only do the insects transport the material from one part of the surface to another, but they burrow among the decayed rocks, which in some tropical regions are decomposed with comparative rapidity. Mr. Branner describes holes made by them to a depth of ten or even thirteen feet from the surface in disintegrated rock at Theóphilo Ottoni, in Brazil, and he points out that their long ramifying underground passages and their shifting of the soil must contribute to the general waste of the country.

Even more remarkable are the geological labours of the termite or white-ant. In tropical Africa this creature builds up crowds of small hills or mounds thirty or forty feet in diameter and ten or fifteen in height, visible at a distance of some miles.[4] So large an amount of fine earth is aggregated in them, that "the brick houses of the Scottish

[1] Murray and Renard, "Deep-Sea Deposits," pp. 378-391. L. Cayeux, *Étude microg. Terr. sédim.* chap. iv.

[2] N. Androussow, as cited on p. 47.

[3] J. C. Branner, *Bull. Geol. Soc. Amer.* vii. (1896), p. 295; *Journ. Geol.* viii. (1900), p. 151.

mission-station on Lake Nyassa were all built out of a single ant's nest, and the quarry from which the material has been derived forms a pit beside the settlement some dozen feet in depth." Besides piling up these edifices, the termites construct out of fine soil tunnels, which they make sometimes on the ground, but more usually on trees, which are thus covered even to the tips of the farthest branches. Millions of trees are fantastically plastered over with tubes, galleries and chambers of earth, and many pounds' weight of subsoil must be brought up even for the mining of a single tree.[1] The removal of so much fine material to the upper air, and the honeycombing of the ground underneath, cannot but facilitate the progressive decay of the rocks, and with the co-operation of wind and rain must promote the general degradation of the surface.

In concluding this account of the deposits which are due mainly to the action of organisms or of organic matter, it may be remarked that the chemistry of some of the processes of precipitation in the sea is still imperfectly understood. The lime so abundantly secreted by calcareous organisms is probably not derived from the comparatively minute quantity of calcium carbonate present in sea-water, but, as we have seen, may be obtained from the far more abundant sulphate by a transformation within the bodies of the living organisms. This chemical process must be one of the most gigantic of all those which are taking place in the ocean. Again, the production of iron-sulphide over such vast areas as are covered by the blue muds is a chemical change which could not be effected without the co-operation of organisms. The precipitation of manganic oxide and its segregation in concretions, often round organic centres, is another widespread chemical process, dependent on organic changes and presenting a close analogy to the formation of concretionary bog-iron ore, through the operation of the humus acids in stagnant water on land. The production of phosphatic deposition and the transformation of silicates of alumina into phosphates of that substance, likewise the precipitation of glauconite, are further manifestations of the important part taken by living and dead organisms in the chemistry of the sea-floor. It is true that as yet no aggregates of silica have been detected in the sea, like the flints which have been so fruitful a source of controversy. Yet the constant association of flints with traces, more or less marked, of former abundant siliceous organisms seems to make the inference irresistible, that the substance of the flint has been precipitated through the agency of these creatures. The silica has been first abstracted from suspended clay or from sea-water by living organisms. It has then been re-dissolved and re-deposited in a colloid form, sometimes in amorphous concretions, sometimes replacing the calcareous parts of echini, mollusks, &c., while the surrounding matrix was, doubtless, still a soft watery ooze under the sea.[2] The production of abundant crystals of

[1] Henry Drummond's 'Tropical Africa,' 1888, chap. vi.

[2] See Wallich, *Q. J. G. S.* xxxvi. p. 68; Sollas, *Ann. Mag. Nat. Hist.* 5th series, vi. p. 437; and *ante*, pp. 179, 612; *Brit. Assoc.* 1882, Sects. p. 549; Hull and Hardman, *Trans. Roy. Dublin Soc.* new series (1878), vol. i. p. 71. Julien observes that a substance

zeolite on the sea-bottom where the water has a temperature a little below or above the freezing-point, is certainly one of the most curious chemical changes which modern research has brought to light. The explanation of it offered by Messrs. Murray and Renard has already been cited. The observations of Lacroix that zeolites may be formed on land even in snow-water, indicate that the low temperature of the sea-floor offers no valid objection to the conclusions of the *Challenger* observers.

## § 4. Man as a Geological Agent.

No survey of the geological workings of plant and animal life upon the surface of the globe can be complete which does not take account of the influence of man—an influence of enormous and increasing consequence in physical geography; for man has introduced, as it were, an element of antagonism to nature. Not content with gathering the fruits and capturing the animals which she has offered for his sustenance, he has, with advancing civilisation, engaged in a contest to subdue the earth and possess it. His warfare, indeed, has often been a blind one, successful for the moment, but leading to sure and sad disaster. He has, for instance, stripped off the woodland from many a region of hill and mountain, gaining his immediate object in the possession of their stores of timber, but thereby laying bare the slopes to parching droughts or fierce rains. Countries once rich in beauty, and plenteous in all that was needful for his support, are now burnt and barren, or washed bare of their soil. It is only in comparatively recent years that he has learnt the truth of the aphorism—"*Homo Naturæ minister et interpres.*"

But now, when that truth is coming more and more to be recognised and acted on, man's influence is none the less marked. His object still is to subdue the earth, and he attains it, not by setting nature and her laws at defiance, but by enlisting her in his service. Within the compass of this volume it is impossible to give more than merely a brief outline of so vast a subject.[1] The action of man is necessarily confined mainly to the land, though it has also to some extent influenced the marine fauna. It may be witnessed on climate, on the flow of water, on the character of the terrestrial surface, and on the distribution of life.

corresponding to humus appears to enter universally into the constitution of the oceanic oozes, resulting from the decomposition of organisms and containing a high percentage of silica (*Proc. Amer. Assoc.* xxviii. p. 359). Consult also the paper of Messrs. Murray and Irvine already cited (*Proc. Roy. Soc. Edin.* xviii. (1891), p. 229), and the suggestive experiments there described as to the solution of silica in sea-water containing living and dead organisms.

[1] See Marsh's 'Man and Nature,' a work which, as its title denotes, specially treats of this subject, and of which a new and enlarged edition was published in 1874 under the title of 'The Earth as modified by Human Action.' It contains a copious bibliography. See also Rolleston, *Jour. Roy. Geog. Soc.* xlix. p. 320, and works cited by him, particularly De Candolle, 'Géographie botanique raisonnée,' 1855; Unger's "Botanische Streifzüge," in *Sitzber. Wiener Acad.* 1857-59; J. G. St. Hilaire, 'Histoire naturelle générale des Règnes organiques,' tom. iii. 1862; Oscar Peschel, 'Physische Erdkunde'; Link, 'Urwelt und Alterthum' (1822); G. A. Koch, *Jahrb. Geol. Reichsanst.* xxv. (1875), p. 114.

1. On Climate.—Human interference affects meteorological conditions—(1) by removing forests and laying bare to the sun and winds areas which were previously kept cool and damp under trees, or which, lying on the lee side, were protected from tempests; as already stated, it is supposed that the wholesale destruction of the woodlands formerly existing in countries bordering the Mediterranean has been in part the cause of the present desiccation of these districts, while in the Tyrol the great increase and destructiveness of the debacles has been attributed to the wholesale deforesting of that region, and the consequent exposure of the soil to rain and melted snow; (2) by drainage, the effect of this operation being to remove rapidly the discharged rainfall, to raise the temperature of the soil, to lessen the evaporation, and thereby to diminish the rainfall and somewhat increase the general temperature of a country; (3) by the other processes of agriculture, such as the transformation of moor and bog into cultivated land, and the clothing of bare hillsides with green crops or plantations of coniferous and hard-wood trees.

2. On the Flow of Water.—(1) By increasing or diminishing the rainfall, man directly affects the circulation of water over the land. (2) By the drainage-operations, which cause the rain to run off more rapidly than before, he increases floods in rivers. (3) By wells, bores, mines or other subterranean works, he interferes with underground waters and consequently with the discharge of springs. (4) By embanking rivers, he confines them to narrow channels, sometimes increasing their scour and enabling them to carry their sediment farther seaward, sometimes causing them to deposit it over the plains and raise their level.

3. On the Surface of the Land.—Man's operations alter the aspect of a country in many ways:—(1) by changing forest into bare mountain, or clothing bare mountain with forest; (2) by promoting the growth or causing the removal of peat-mosses; (3) by heedlessly uncovering sand-dunes, and thereby setting in motion a process of destruction which may convert hundreds of acres of fertile land into waste sand, or by prudently planting the dunes with sand-loving herbage or pines, and thus arresting their landward progress; (4) by so guiding the course of rivers as to make them aid him in reclaiming waste land and bringing it under cultivation; (5) by piers and bulwarks, whereby the ravages of the sea are stayed, or by the thoughtless removal from the beach of stones which the waves had themselves thrown up, and which would have served for a time to protect the land; (6) by forming new deposits either designedly or incidentally. The roads, bridges, canals, railways, tunnels, villages and towns with which man has covered the surface of the land will in many cases form a permanent record of his presence. Under his hand, the whole surface of civilised countries is very slowly covered by a stratum, either formed wholly by him, or due in great measure to his operations, and containing many relics of his presence. The soil of old cities has been increased to a depth of many feet by the rubbish of his buildings; the level of the streets of modern Rome stands high above that of the pavements of the Cæsars, and this again above the roadways

of the early Republic. Over cultivated fields potsherds are turned up in abundance by the plough. The loam has risen within the walls of our graveyards, as generation after generation has mouldered there into dust.

4. On the Distribution of Life.—It is under this head, perhaps, that the most subtle of human influences come. Some of man's doings in this dominion are indeed plain enough, such as the extirpation of wild animals, the diminution or destruction of some forms of vegetation, the introduction of plants and animals useful to himself, and especially the enormous predominance given by him to the cereals and to the spread of sheep and cattle. But no such extensive disturbance of the normal conditions of the distribution of life can take place without carrying with it many secondary effects, and setting in motion a wide cycle of change and of reaction in the animal and vegetable kingdoms. For example, the incessant warfare waged by man against birds and beasts of prey, in districts given up to the chase, leads sometimes to unforeseen results. The weak game is allowed to live, which would otherwise be killed off and give more room for the healthy remainder. Other animals, which feed perhaps on the same materials as the game, are from the same cause permitted to live unchecked, and thereby to act as a further hindrance to the spread of the protected species. But the indirect results of man's interference with the *régime* of plants and animals still require much prolonged observation.[1]

This outline may suffice to indicate how important is the place filled by man as a geological agent, and how in future ages the traces of his interference may introduce an element of difficulty or uncertainty into the study of geological phenomena.

[1] See on the subject of man's influence on organic nature, the paper by Professor Rolleston, quoted in the previous note, and the numerous authorities cited by him.

# BOOK IV.

## GEOTECTONIC (STRUCTURAL) GEOLOGY,

### OR THE ARCHITECTURE OF THE EARTH'S CRUST.

THE nature of minerals and rocks and the operations of the different agencies by which they are produced and modified having been discussed in the two foregoing books, there remains for consideration the manner in which these materials have been arranged so as to build up the crust of the earth. Since by far the largest visible portion of this crust consists of sedimentary or aqueous rocks, it will be of advantage to treat of them first, noting both their original characters, as resulting from the circumstances under which they were formed, and the modifications subsequently effected upon them. Many superinduced structures, not peculiar to sedimentary, but occurring more or less markedly in all rocks, may be conveniently described together. The distinctive characters of the igneous or eruptive rocks, as portions of the architecture of the crust, will then be described; and lastly, those of the crystalline schists and other associated rocks to which the name of metamorphic is usually applied.

## PART I. STRATIFICATION AND ITS ACCOMPANIMENTS.

The term "stratified," so often applied as a general designation to the aqueous or sedimentary rocks, expresses their leading structural feature. Their materials, laid down for the most part on the bed of the sea, but partly on the floors of lakes and rivers, and even subaerially on dry land, under conditions which have been already discussed in Book III., are disposed in layers or strata, an arrangement characteristic of them alike in hand-specimens and in cliffs and mountains (Figs. 194, 195, 214, 260, and 261). Not that every morsel of aqueous rock exhibits evidence of stratification. But it is this feature which in a sufficiently large mass of material is least frequently absent. The general characters of stratification will be best understood from an explanation of the terms by which they are expressed.

**Forms of Bedding.**—Laminae are the thinnest paper-like layers in the planes of deposit of a stratified rock. Such fine layers only occur where the material is fine-grained, as in mud or shale, or where fine scales of some mineral have been plentifully deposited, as in micaceous sandstone. In some laminated rocks, the laminæ cohere so

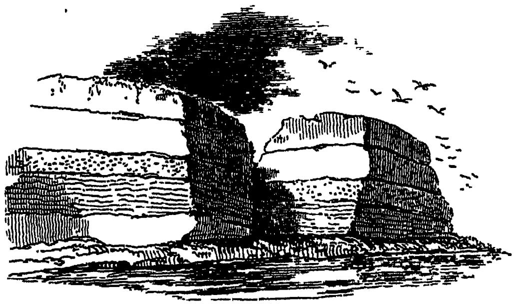


Fig. 194.—Sea-cliff showing a series of Stratified Rocks (*B.*).

firmly that they can hardly be split open, and the rock will break more readily across them than in their direction. More usually, however, the planes of lamination serve as convenient divisional surfaces by means of which the rock can be split open.[1] The cause of this structure has been generally assigned to intermittent deposit, each lamina being assumed to have partially consolidated before its successor was laid down upon it. Mr. Sorby, however, has recently suggested that in fine argillaceous rocks it may be a kind of cleavage-structure (see pp. 417, 684), due to the pressure of the overlying rocks, with the consequent squeezing out of interstitial water and the re-arrangement of the argillaceous particles in lines perpendicular to the pressure.[2]


Fig. 195.—Section of Stratified Rocks. *a*, conglomerate; *b*, thick-bedded pebbly sandstone; *c*, thin-bedded sandstone; *d*, shaley sandstone; *e*, shale with ironstone nodules; *f*, limestone with crinoids and corals.

Much may be learnt as to former geographical and geological changes by attending to the characters of strata. In Fig. 195, for example, there is evidence of a gradual diminution of movement in the waters in which the layers of sediment were deposited. The conglomerate (*a*) points to currents of some force; the sandstones (*b c d*) mark a progressive quiescence and the advent of finer sediment; the shales (*e*) show a deposition of fine mud and accretion of ferrous carbonate into nodules round organic remains; while the coral-limestone (*f*) proves that the water no longer carried much sediment, but had become clear

[1] M. Daubrée has proposed the term *diastrome* to express the splitting of rocks along their bedding-places. *Bull. Soc. Géol. France* (3), x. p. 137.

[2] *Quart. Journ. Geol. Soc.* xxxvi. (1880), p. 67.

enough for an abundant growth of marine organisms. The existence, therefore, of alternations of fine laminæ of deposit may be conceived as pointing to tranquil conditions of slow intermittent sedimentation, where silt has been borne at intervals and has fallen over the same area of undisturbed water. Regularity of thickness and persistence of lithological characters among the laminæ may be taken to indicate periodic currents, of approximately equal force, from the same quarter. In some cases, successive tides in a sheltered estuary may have been the agents of deposition. In others, the sediment was doubtless brought by recurring river-floods. A great thickness of laminated rock, like the massive shales of Palæozoic formations, suggests a prolonged period of quiescence, and probably, in most cases, slow, tranquil subsidence of the sea-floor. On the other hand, the alternation of thin bands of laminated rock with others coarser in texture and non-laminated, indicates considerable oscillation of currents from different quarters bearing various qualities and amounts of sediment.[1]

Strata or Beds are layers of rock varying from an inch or less up to many feet in thickness. A stratum may be made up of numerous laminæ, if the nature of the sediment and mode of deposit have favoured the production of this structure, as has commonly been the case with the finer kinds of sediment. In materials of coarser grain, the strata, as a rule, are not laminated, but form the thinnest parallel divisions. Strata, like laminæ, sometimes cohere firmly, but are commonly separable with more or less ease from each other. In the former case, we may suppose that the lower bed, before consolidation, was followed by the deposit of the upper. The common merging of a stratum into that which overlies it must no doubt be regarded as evidence of more or less gradual change in the conditions of deposit. Where the overlying bed is abruptly separable from that below it, the interval was probably of some duration, though occasionally the want of cohesion may arise from the nature of the sediment, as, for instance, where an intervening layer of mica-flakes has been laid down. A stratum may be one of a series of similar beds in the same mass of rock, as where a thick sandstone includes many individual strata, varying considerably in their respective thicknesses; or it may be complete and distinct in itself, as where a band of limestone or ironstone runs through the heart of a series of shales. As a general rule, the conclusion appears to be legitimate that stratification, when exceedingly well-marked, indicates slow intermittent deposition, and that when weak or absent, it points to more rapid deposition, intervals and changes in the nature of the sediment and in the direction of force of the transporting currents being necessary for the production of a distinctly stratified structure.

Lines due to original stratification must be carefully distinguished from other divisional planes which, though somewhat like them, are of entirely different origin. Six kinds of fissility may be recognised among

[1] For a series of experiments to illustrate the origin of the sedimentation of the Coal-measures, see H. Fayol, *Bull. Soc. Industrie Minérale, St. Étienne*, 2me sér. xv. (1886): "Études sur le Terrain houiller de Commentry," with atlas.

rocks:—1st, *lamination* of original deposit; 2nd, *jointing*, which, when the planes of division are set close to each other, causes the rocks to split into parallel slabs or blocks (p. 658); 3rd, *cleavage*, as in slate (pp. 417, 684); 4th, *shearing*, as near faults and thrust-planes (pp. 419, 681); 5th, *foliation*, as in schists (p. 244); 6th, *flow-structure*, which when extremely developed in lavas produces a kind of fissility resembling the lamination of deposit.

Originally the planes of stratification, in the great majority of cases, were nearly horizontal. As most sedimentary rocks are of marine origin, and have accumulated on the shallower slopes of the sea-floor, they have generally had from the first a gentle inclination seawards; but, save on rapidly shelving shores, the angle of declivity has been usually so low as to be hardly appreciable by the eye. Departures from this predominant horizontality would be caused where sediment accumulated on subaqueous talus-slopes, as at the base of cliffs, or where the floor on which deposition took place was of an undulating or more markedly uneven character.

False-bedding, Current-bedding.—Some strata, particularly sandstones, are marked by an irregular lamination, wherein the laminæ, though for short distances parallel to each other, are oblique to the general stratification of the mass, at constantly varying angles and in different directions (*a b c d* in Fig. 196). This structure, known as false-bedding or current-bedding, points to frequent changes in the direction of the currents by which the sediment was carried along and deposited. Sand pushed over the bottom of a sheet of water by varying currents tends to be laid down irregularly in banks and ridges, which often advance with a steep slope in front. The upper and lower surfaces of the bank or bed of sand (* * in Fig. 196) may remain parallel with each other as well as with the underlying bottom (*a*), yet the successive laminæ composing it may lie at an angle of 30° or even more.

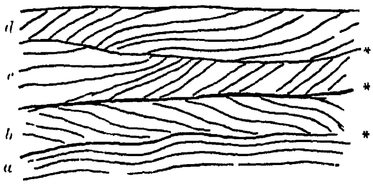


Fig. 196.—Section of False-bedded Strata.

We may illustrate this structure by the familiar formation of a railway embankment. The top of the embankment, on which the permanent way is to be laid, is kept level; but the advancing end of the earthwork shows a steep slope over which the workmen are constantly discharging waggon-loads of rubbish. Hence the embankment, if cut open longitudinally, would present a "false-bedded" structure, for it would be found to consist of many irregular layers inclined at high angles in the direction in which the formation of the mound had advanced. Among geological formations of all ages, occasional sections of the upper surfaces of such false-bedded strata show the singular irregularity of the structure, and bring vividly before the imagination the feeble shifting currents by which the sediment was drifted about in the shallow water where it accumulated (Fig. 197). A noticeable feature is the markedly lenticular character of false-bedded strata. Even where the usual diagonal lamination is feeble or absent, this lenticular structure may remain distinct (Fig. 198). Examples may also be observed, in which, while all the beds are well laminated, in some the laminæ run parallel with the general bedding, and in others obliquely to it (Fig. 199). Though current-

bedding is most frequent among sandstones, or markedly arenaceous strata, it may be observed occasionally in detrital formations of organic origin, as shown in a section (Fig. 200) by De la Beche, where a portion of one of the calcareous members of the Jurassic series of England consists of beds composed mostly of organic fragments with a strongly

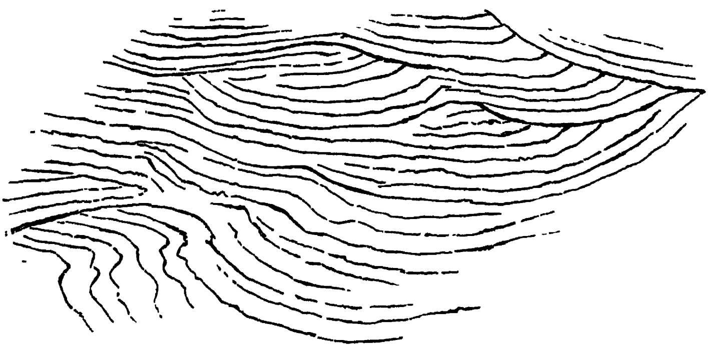


Fig. 197.—Plan of upper surface of a False-bedded Coal-measure Sandstone, Nolton Haven, Pembrokeshire. (John Phillips.)

marked current-bedding (*a a*), while others, formed of muddy layers and not obliquely laminated (*b b*), point to intervals when, with the cessation of the silt-bearing currents, the water became still enough to allow the mud suspended in it to settle on the bottom.[1]

Intercalated Contortion.—Diagonal lamination is sometimes contorted as well as steeply inclined, and highly contorted beds are interposed between others which are undisturbed and horizontal. Curved

Fig. 198.—False-bedded Strata, Old Red Sandstone, Ross, Herefordshire. (Sir Henry James, R.E.)

and contorted lamination is of frequent occurrence among Palæozoic sandstones. In Fig. 201, an example is given from one of the oldest formations in Britain, and in Fig. 202 another from one of the youngest. In the Calciferous Sandstones of East Fife, the structure is abundant in

[1] 'Geological Observer,' p. 536. The memoir by H. Fayol, cited on p. 635, is accompanied with an atlas which contains many excellent illustrations of the exceedingly irregular stratification of the Coal-measures. See also G. K. Gilbert, "Ripple-marks and Cross-bedding," *Bull. Am. Geol. Soc.* x. (1899), p. 135.

the thicker beds of sandstone intercalated among rapid alternations of perfectly undisturbed parallel seams of shale, coal and limestone. The cause of this structure is not well understood. Among glacial deposits

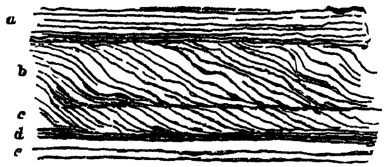



Fig. 199.—Ordinary Lamination and Current-lamination, Upper Old Red Sandstone, Clowes Bay, Waterford (*B.*).
*a*, *d*, *e*, beds of sand and silt deposited horizontally and apparently from mechanical suspension; *b*, *c*, beds of sand which have been pushed along the bottom.

local examples of contortion occur, which may be accounted for by the intercalation and subsequent melting of sheets of frozen mud, or by the stranding of heavy masses of drift-ice upon still unconsolidated sand and

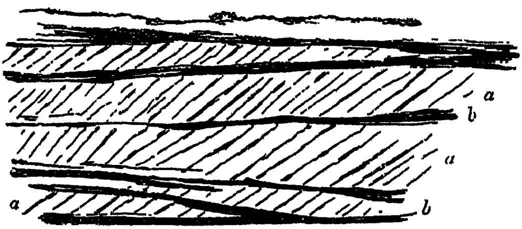



Fig. 200.—Section in the Forest Marble, the Butts, Frome, Somerset (*B.*).
*a*, *a*, beds formed of broken shells, fish-teeth, pieces of wood, and oolitic grains; *b*, *b*, layers of clay.

mud. The removal of mineral matter in solution (as among saliferous and gypseous deposits) leads to the subsidence and crumpling of overlying beds. The hydration of anhydrite (pp. 400, 453), by augmenting

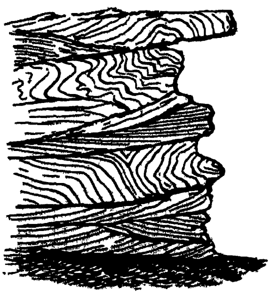


Fig. 201.—Contorted False-bedding, Torridon Sandstone, Gairloch.

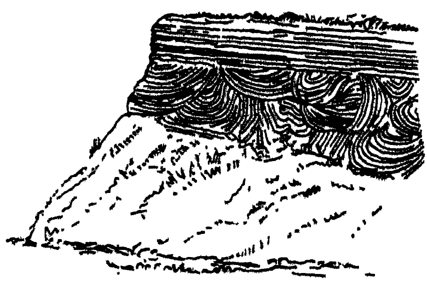


Fig. 202.—Contorted Post-Tertiary Sands and Clays, near Forres.

the volume of the mass, subjects the adjacent strata to crushing and contortion. It is possible that some of the extraordinary labyrinthine and complex contortions of certain schistose rocks may be due to the

subsequent crumpling of strata already full of diagonal or contorted lamination.

Irregularities of Bedding due to Inequalities of Deposition or of Erosion.—A sharp ridge of sand or gravel may be laid down under water by current-action of some strength. Should the motion of the water diminish, finer sediment may be brought to the place and be deposited around and above the ridge. In such a case, the stratification of the later accumulation may end off abruptly against the flanks of the older ridge, which will appear to rise up through the younger sediment. Appearances of this kind are not uncommon in coal-fields, where they are known to the miners as "rolls," "swells," or "horses' backs." A structure exactly the reverse of the preceding, where a stratum has been scooped out before the deposition of the layers which cover it, has also often been observed in mining for coal, when it is termed a "wash-out" or "want."

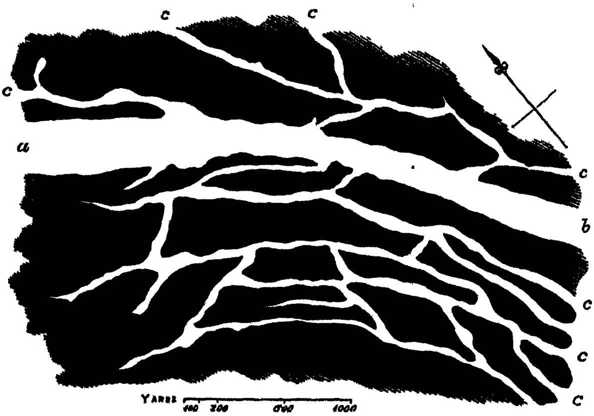



Fig. 203.—Plan of Channels in Coal, Forest of Dean (after Buddle).

Channels have been cut out of a coal-seam, or rather out of the bed of vegetation which ultimately became coal, and these winding and branching channels have been filled up with sandy or muddy sediment. The accompanying plan (Fig. 203) represents a portion of a remarkable series of such channels traversing the Coleford High Delf coal-seam in the Forest of Dean. The chief one, locally known as the "Horse" (*a b*), has been traced for about two miles, and varies in width from 170 to 340 yards. It is joined by smaller tributaries (*c c*), which run for some way approximately parallel to it. The coal has either been prevented from accumulating in contemporaneous water-channels, or, while still in the condition of soft bog-like vegetation, has been eroded by streamlets flowing through it.[1] A section drawn across such a buried channel exhibits the structure represented in Fig. 204, where a bed of fire-clay (*e*), full of roots and evidently an old soil, supports a bed of coal (*d*) and of shale (*c*), which, during the deposition of this series of strata, have been cut out into a channel at *f*. A deposition of sand (*b*) has then filled up the excavation, and a layer of mud (*a*) has covered up the whole.

Currents of very unequal force and transporting power may alternate in such a way

[1] Buddle, *Geol. Trans.* vi. (1842), p. 215.

that after fine silt has for some time been accumulated, coarse shingle may next be swept along, and may be so irregularly bedded with the softer strata as to simulate the behaviour of an intrusive rock (Fig. 205).[1] The section (Fig. 206) taken by De la Beche from a cliff of Coal-measures on the coast of Pembrokeshire, shows a deposit of shale

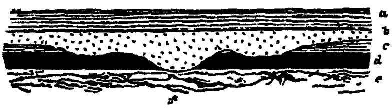



Fig. 204.—Section of a Channel in a Coal-seam (*B.*).

(*a*) that during the course of its formation was eroded by a channel at *b*, into which sand was carried; after which, the deposit of fine mud recommenced, and similar shale was again laid down upon the top of the sandy layer, until, by a more potent current, the shale deposit was cut away on the left side of the section, and a series of sandbeds

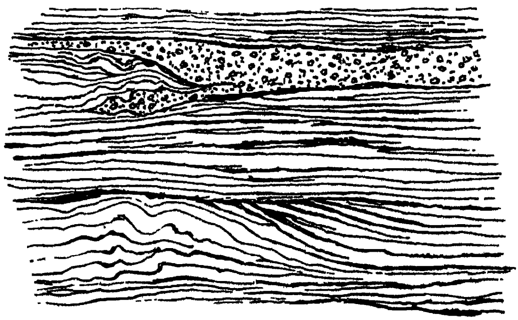


Fig. 205.—Irregular Bedding of coarse and fine Lower Silurian detritus, Flanks of Glydyr, N.E. of Snowdon (*B.*).

(*c*) was laid down upon its eroded edges. An interruption of this kind, however, may not seriously disturb the earlier conditions of a deposit, which, as shown in the same section, may be again resumed, and new layers (*d*) may be laid down conformably over the whole. Among the lessons to be learnt from such sections of local irregularity, one

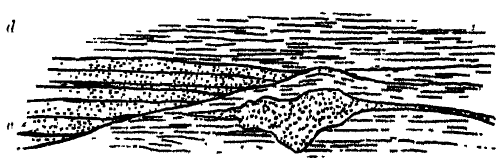



Fig. 206.—Contemporaneous Erosion and Deposit (*B.*).

of the most useful is the reminder that the inclination of strata may not always be due to subterranean movement. In Fig. 207, for example, the lower strata of shale and sandstone are nearly horizontal. The upper thick sandstone (*b′*) has been cut away towards the left, and a series of shales (*a′*) and a coal-seam (*c′*) have been deposited against and over it. If the sandstone was then level, the shales must have been laid down at a considerable angle, or, if these were deposited in horizontal sheets, the earlier

[1] De la Beche, 'Geol. Observer,' p. 583. But see the following remarks on overthrust faults in the Coal-measures.

sandstone must have accumulated on a marked slope. As deposition continued, the inclined plane of sedimentation would gradually become horizontal until the strata were once more parallel with the series *a b c* below. A structure of this kind, not infrequent in the Coal-measures, must be looked upon as a larger kind of false-bedding, where, however, terrestrial movement may sometimes have intervened.

In the instances here cited, it is evident that the erosion took place, in a general sense, during the same period with the accumulation of the strata. For, after the interruption was covered up, sedimentation went on as before, and there is usually an obvious close sequence between the continuous strata. Though it may be impossible to decide as to the relative length of the interval that elapsed between the formation of a given stratum and that of the next stratum which lies upon its eroded surface, or to ascertain how much depth of rock has been removed in the erosion, yet, when the structure occurs among conformable strata, evidently united as one lithologically continuous series of deposits, we may reasonably infer that the missing portions are of small

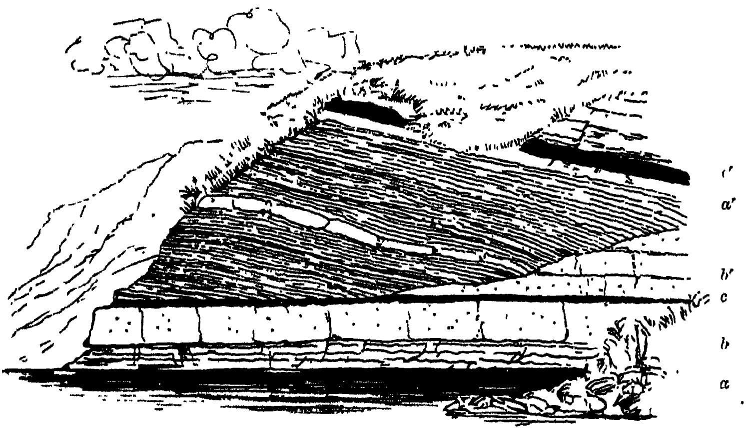



Fig. 207.—Contemporaneous Erosion with inclined and horizontal deposits, in Coal-measures, Kello Water, Sanquhar, Dumfriesshire.
*a*, *a'*, shales and ironstones; *b*, *b'*, sandstones; *c*, *c'*, coal-seams.

moment, and that the erosion was merely due to the irregular and more violent action of the very currents by which the sediment of the successive strata was supplied.

The case is different when the eroded strata, besides being inclined at a different angle from those above them, are strongly marked off by lithological distinctions, particularly when fragments of them occur in the overlying deposits. In some of the coal-mines in Central Scotland, for instance, deep channels have been met with entirely filled with sand, gravel or clay belonging to the general superficial drift of the country. These channels have evidently been water-courses worn out of the Coal-measure strata at a comparatively recent geological period, and subsequently buried under glacial accumulations. There is a complete discordance between them and the Palæozoic strata below, pointing to the existence of a vast interval of time (see under Unconformability, p. 820 *et seq.*).

The recent progress of research has shown that overthrust faults, which are much more frequent than was formerly supposed, may sometimes produce effects not greatly different from those here described. Indeed, it is not improbable that instances which have been looked upon as exemplifying contemporaneous erosion or deposit, such as some of the "horses" and "wash-outs" of the Coal-measures, may really be due to the effect of such reversed faults. In Fig. 206, for example, it is conceivable that the diagonal

line of separation drawn by De la Beche may mark a reversed fault, and that the overlying sandstones (*c*) are really a lower part of the series pushed upward over (*a*) by an over-thrust.[1]

**Surface-markings.**—The surface of many beds of sandstone is marked with lines of wavy ridge and hollow, such as may be seen on a sandy shore from which the tide has retired, on the floors of shallow lakes and of river-pools, and on surfaces of dry wind-blown sand. To these markings the general name of Ripple-mark has been given. They have been produced by an oscillation of the medium (water or air) in which the loose sand has lain. In water, an oscillatory movement, sometimes also with a more or less marked current, is generated by wind blowing on its surface. The sand-grains are carried backwards and forwards. By degrees, inequalities of surface are produced, which give rise to vortices in the water. In irregular ripple-mark, the direct current carries the

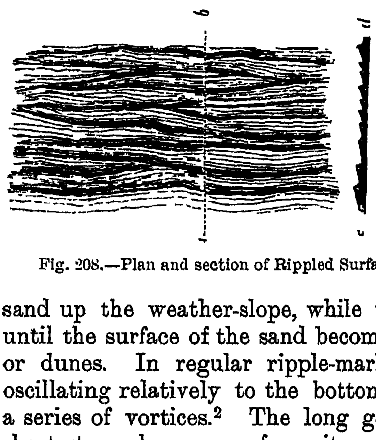


Fig. 208.—Plan and section of Rippled Surface.

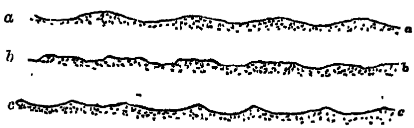



Fig. 209.—Sections of Ripple-marks.

sand up the weather-slope, while the vortex pushes it up the lee-slope, until the surface of the sand becomes mottled over with little prominences or dunes. In regular ripple-mark, the forms are produced by water oscillating relatively to the bottom and the consequent establishment of a series of vortices.[2] The long gentle slope towards the wind, and the short steep slope away from it, are well marked (Fig. 208, compare also Fig. 91). Considerable diversity in the form of the ripple, however, may be observed (as at *a b c* in Fig. 209), depending on conditions of wind, water and sediment which have not been thoroughly studied. No satisfactory inference can be drawn from the existence of ripple-marks as to the precise depth of water in which the sediment was accumulated. As a rule, it is in water of only a few feet or yards in depth that this characteristic surface is formed. But it may be produced at any depth to which the agitation caused by wind on the upper waters may extend (p. 562). Examples of it may be observed among arenaceous deposits of all ages from pre-Cambrian upwards. In like manner, we may frequently detect

[1] See a paper on overthrusts and other disturbances in the Radstock series of the Somerset Coal-field, by F. A. Steart, *Q. J. G. S.* lviii. (1902).

[2] Professor Darwin, *Proc. Roy. Soc.* xxxvi. (1883), p. 18. See also H. C. Sorby, *Edin. New Phil. Journ.* new ser. iii. iv. v. vii. ; *Geologist,* ii. (1859), p. 137 ; A. R. Hunt, *Proc. Roy. Soc.* xxxiv. p. 1 ; C. de Candolle, *Arch. Sci. Phys. Nat. Genève,* ix. (1883) ; M. Forel, in same volume ; Gosselet, *Ann. Soc. Géol. Nord,* ix. (1882), p. 76 ; G. K. Gilbert's paper cited *ante,* p. 637.

among these formations, small isolated or connected linear ridges (rill-marks) directed from some common quarter, like the current-marks frequently to be found behind projecting fragments of shell, stones or bits of seaweed on a beach from which the tide has just retired.

On an ordinary beach, each tide usually effaces the ripple-marks made by its predecessor, and leaves a new series to be obliterated by the next tide. In the process of obliteration, the tops of the ridges are levelled off (see *b* in Fig. 209), while sometimes the hollows, where they serve as receptacles for surface drainage, are deepened. Where the markings are formed in water which is always receiving fresh accumulations of sediment, a rippled surface may be gently overspread by the descent of a layer of sediment upon it, and may thus be preserved. By a renewal of the oscillation of the water another series of ripples may then be made in the overlying layers, which in turn may be buried and preserved under a renewed deposit of sand. In this way, a considerable thickness of such ripple-marked strata may be accumulated, as has frequently taken place among geological formations of all ages.

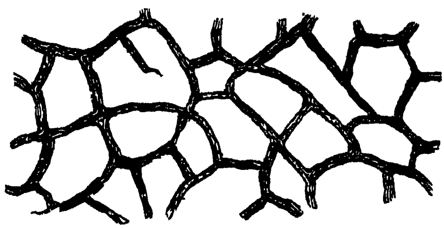


Fig. 210.—Sun-cracked Surface of Mud or Muddy Sand.

Sun-cracks, Rain-prints, Vestiges of former Shores.—One of the most fascinating parts of the work of a field-geologist consists in tracing the shores of former seas and lakes, and in endeavouring thereby to reconstruct the geography of successive geological periods. There are not a few pieces of evidence which, though in themselves individually of apparently small moment, combine to supply him with reliable data. Among these he lays special emphasis upon the proofs that, during their deposition, strata have at intervals been laid bare to sun and air.

The nature and validity of the arguments founded on this evidence will be best realised by the student if he can make observations at the margin of the sea, or of any inland sheet of water, which from time to time leaves tracts of mud or fine sand exposed to sun and rain. The way in which the muddy bottom of a dried-up pool cracks into polygonal cakes when exposed to the sun may be illustrated abundantly among sedimentary rocks. These desiccation-cracks, or sun-cracks (Fig. 210), could not have been produced so long as the sediment lay under water. Their existence therefore among any strata proves that the surface of rock on which they lie was exposed to the air and dried, before the next layer of water-borne sediment was deposited upon it.

With these markings are occasionally associated prints of rain-drops.

The familiar effects of a heavy shower upon a surface of moist sand or mud may be witnessed among rocks even as old as the Cambrian period. In some cases, the rain-prints are found to be ridged up on one side, in such a manner as to indicate that the rain-drops as they fell were driven

Fig. 211.—Footprints from the Triassic Sandstone of Connecticut (Hitchcock).

aslant by the wind. The prominent side of the markings, therefore, indicates the side towards which the wind blew.

Numerous proofs of shallow shore-water, and likewise of exposure to the air, are supplied by markings left by animals. Castings, tubular burrows and trails of worms, tracks of mollusks and crustaceans, fin-marks of fishes, footprints of reptiles, birds and mammals (Figs. 211, 212), may

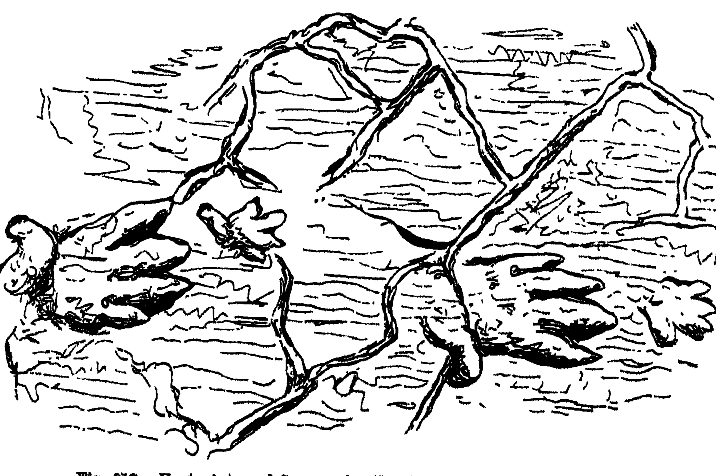


Fig. 212.—Footprints and Sun-cracks, Hildburghausen, Saxony (Sickler).

all be preserved and give their evidence regarding the physical conditions under which sedimentary formations were accumulated. It may frequently be noticed that such impressions are associated with ripple-marks, rain-prints or sun-cracks; so that more than one kind of evidence may be gleaned from a locality to show that it was sometimes laid bare of water.

The more striking indications of littoral conditions being comparatively infrequent, the geologist must usually content himself with tracing the gravelly detritus, which suggests, if it does not always prove, proximity to some former line of shore. Such a section, for instance, as that depicted in Fig. 213 may often be found, where lower strata (*a*) having been tilted, raised into land, and worn away, have yielded materials for a coarse littoral boulder-bed (*b*), over which, as it was carried down into deeper and clearer water, limestone eventually accumulated. Beds of conglomerate, especially where, as in this example, they accompany an unconformability in the stratification, are of much service in tracing the limits of ancient seas and lakes (see Part X., p. 820).

Gas-spurts.—The surfaces of some strata, usually of a dark colour and containing organic matter, may be observed to be raised into little heaps of various indefinite shapes, not like the heaps associated with worm-burrows, connected with pipes descending into the rock, nor composed of different material from the surrounding sandstone or shale.

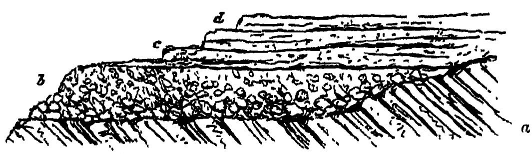



Fig. 213.—Section of a Beach of early Mesozoic age, near Clifton, Bristol (*B.*).

*a*, carboniferous limestone ; *b*, dolomitic conglomerate—a mass of boulders and angular fragments of *a* (some of them almost two tons in weight), passing up into finer conglomerate *c*, with sandstone and marl, and thence into dolomitic limestone *d*.

These may be conjectured to be due to the intermittent escape of gas from decomposing organic matter in the original sand or mud, as we may sometimes witness in operation among the mud-flats of rivers and estuaries, where much organic matter is decomposing among the sediment. On a small scale, these protrusions of the upper surface of a deposit may be compared with the mud-lumps at the mouths of the Mississippi, already described (p. 512).

Surface-markings due to Movement.—The older rocks, which have been longest exposed to disturbances of the crust, not infrequently present on the surfaces of some of their strata curiously ridged or branching protuberances. These markings are especially to be seen on the surfaces of shales or other layers of comparatively soft material intercalated among harder and more massive rocks, such as greywackes or sandstone. They occasionally simulate organic forms, and have even been described as fossil sea-weeds, to which their branching arrangement occasionally offers a remarkably strong resemblance. There can be little doubt, however, that in a large number, probably the vast majority of cases, these radiating wrinkles and other markings are entirely of inorganic origin, and have been the result of differential movements of the strata under intense strain, and are most marked in the shales, because these strata would naturally yield most readily. They may be imitated arti-

ficially by introducing a layer of some viscous substance between two plates of glass, which are afterwards pressed together or moved one over the other.[1]

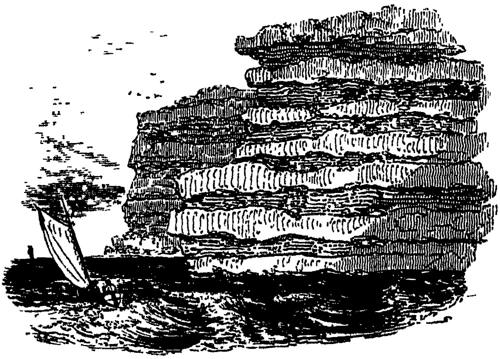


Fig. 214.—Section of alternations of Shale and Concretionary Limestone (*B.*).

**Concretions.**—Many sedimentary rocks, more particularly clays, ironstones and limestones, exhibit a concretionary structure. This arrangement may be part of the original sedimentation, or may be due to subsequent segregation from decomposition round a centre. Concretionary structures, particularly in calcareous materials, may lie so closely adjacent as to form continuous or nearly continuous beds (Fig. 214). The Magnesian Limestone of Durham is built

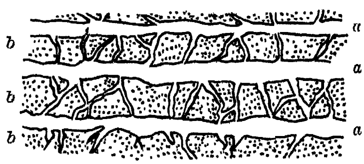



Fig. 215.—Sections of beds and connecting strings of Gypsum in the Trias, Watchet, Somersetshire (*B.*).

up of variously shaped concretionary masses, sometimes like cannon-balls, grape-shot or bunches of coral. Connected with concretionary beds are the seams of gypsum, which may occasionally be observed to send out veins into other gypsum beds above and below them. De la Beche describes a section at Watchet, Somersetshire, where, amid the Triassic

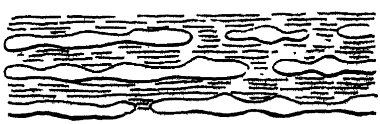


Fig. 216.—Concretions of Limestone in Shale.

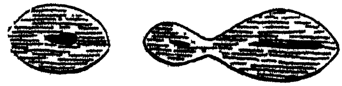


Fig. 217.—Concretions surrounding organic centres and exhibiting the continuation of the lines of stratification of the surrounding shales.

marls (*b b* in Fig. 215), seams of gypsum (*a a*) connect themselves by means of fibrous veins with the overlying and underlying beds.

[1] A. G. Nathorst, 'Nouvelles Observations sur les Traces d'Animaux, &c.' 4to, Stockholm, 1886; A. Issel, "Impressions radiculaires et Figures de Viscosité ayant l'apparence de Fossiles," *Bull. Soc. Belg. Géol.* iii. (1889), p. 450.

The most frequent form of concretions is that of isolated spherical, elliptical or variously shaped nodules, disposed in certain layers of a stratum or dispersed irregularly through it (Fig. 216). They most commonly consist of ferrous or calcic carbonates, or of silica. Many clay-ironstone beds assume a nodular form, and this mineral occurs abundantly as separate nodules in shales and clay-rocks (Sphærosiderite). The nodules have frequently been formed round some organic body, such as a fragment of plant, a shell, bone, or coprolite. That the carbonate was slowly precipitated during the formation of the enclosing bed of shale, may often be satisfactorily proved by the lines of deposit passing continuously through the nodules (Fig. 217). In many cases, the internal first-formed parts of a nodule have contracted more than the outer and more compact crust, and have cracked into open polygonal spaces, which are commonly filled with calcite

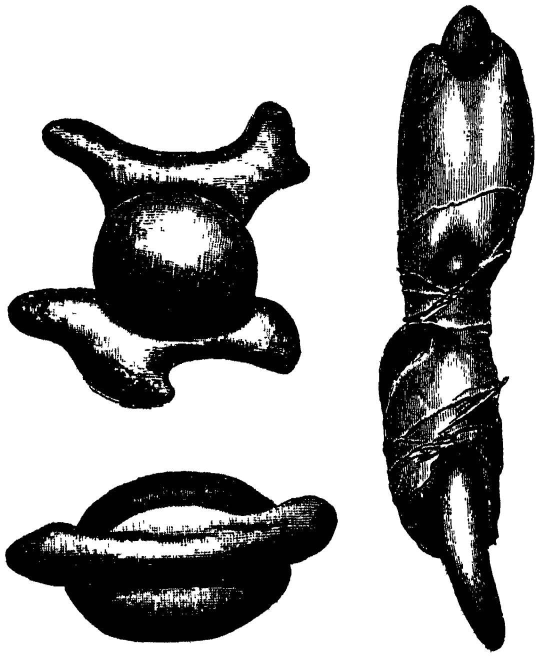


Fig. 218.—Clay concretions of Alluvium (nat. size).

(Fig. 25). Such *septarian nodules*, whether composed of clay-ironstone or limestone, are abundant in many shales, as in the Carboniferous and Liassic series of England.

Alluvial clays sometimes contain fantastically shaped concretions due to the consolidation of the clay by a calcareous or ferruginous cement round a centre. These are known in Scotland as Fairy-stones, in the valley of the Rhine as Lösspuppen, Lössmänchen, and in Finland as Imatra-stones (Fig. 218 and p. 489). They not uncommonly show the bedding of the clay in which they may have been formed. Their quaint imitative forms have naturally given rise to a popular belief that they are petrifactions of various kinds of organic bodies and even of articles of human manufacture. In Norway they occur in glacial and post-glacial deposits up to heights of 360 feet above sea-level, and enclose remains of fishes (of which 16 species have been noticed), as well as other organisms.[1]

[1] Kjerulf, 'Geologie des südl. und mittl. Norwegens' (1880), p. 5; R. Collet, *Nyt. Mag.* xxiii. No. 3, p. 11. The most voluminous account of such alluvial concretions will be

Concretions of silica occur in limestone of many geological ages (p. 624). The flints of the English Chalk are a familiar example, but similar siliceous concretions occur in Carboniferous and Cambrian limestones. The silica, in these cases, has not infrequently been deposited round organic bodies, such as sponges, sea-urchins and mollusks, which are completely enveloped in it, and have even themselves been silicified. Iron-disulphide often assumes the form of concretions, more particularly among clay-rocks, and these, though presenting many eccentricities of shape—round, like pistol-shot or cannon-balls, kidney-shaped, botryoidal, &c.—agree in usually possessing an internal fibrous radiated structure. Phosphate of lime is found as concretions in formations where the coprolites and bones of reptiles and other animals have been collected together (p. 626).

Concretions produced subsequently to the formation of the rock occur in some sandstones, which, when exposed to the weather, decompose into large round balls. In other instances, a ferruginous cement is gradually aggregated by percolating water in lines which curve round so as to enclose portions of the rock. These lines, owing to abstraction of iron from within the spheroid and partly from without, harden into dark crusts, inside of which the sandstone becomes quite bleached and soft.[1] Some shales exhibit a concretionary structure in a still more striking manner, inasmuch as the concretions consist of the general mass of the laminated shale, and the lines of stratification pass through them and mark them out distinctly as superinduced upon the rock. Examples of this structure are not infrequent among the argillaceous strata of the Carboniferous system. The concretionary olive-green shales and mudstones of the Ludlow group, in the Upper Silurian system, exhibit on weathered surfaces, all the way from South Wales into Central Scotland, a peculiar structure which consists in the development of concentric spheroids varying from less than an inch up to several feet in diameter, the successive shells being separated from each other by a fine dark ferruginous film (Fig. 219). The lines of stratification are sometimes well marked by layers of fossils, but the rock splits up mainly along the curved surfaces separating the concentric shells. Concretionary structures are found also in rocks formed from chemical precipitation, as for instance in beds of rock-salt.

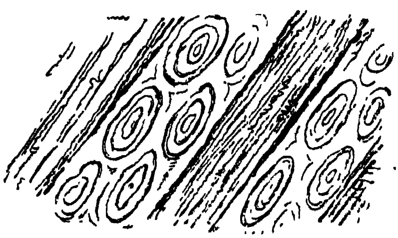


Fig. 219.—Concretionary structure in Upper Silurian Shales, Cwm-ddu, Llangammarch, Brecknockshire (*B.*).

The structure known as "cone-in-cone" has been referred to pressure (p. 421), but in many cases appears rather to be due to a form of crystallisation of the constituent calcite after the deposition of the stratum in which it occurs. The calcium carbonate has crystallised in a number of small cones one within another, forming a succession of sheaths, which include some of the non-crystalline surrounding matrix, and are gradually built up into a conical aggregate or group of such aggregates.[2]

**Dendritic Markings.**—On the divisional planes of fine-grained rocks arborescent deposits of earthy oxides of manganese or of iron are of frequent occurrence (Fig. 220). Their curiously imitative forms have often led to their being mistaken for fossil plants; but like the plumose shapes assumed by ice on frosted windows, they are entirely of

found in a quarto volume by J. M. A. Sheldon, 'Concretions from the Champlain Clays of the Connecticut Valley,' pp. 45, with 160 illustrations, Boston, 1900.

[1] See Penning, *Geol. Mag.* Dec. 2, iii. May 1876; and "Eagle-stones," *ante*, p. 187.

[2] H. C. Sorby, *Brit. Assoc.* 1859, Sects. p. 124; W. S. Gresley, *Q. J. G. S.* xlii. p. 110; G. A. T. Cole, *Mineral. Mag.* x. (1892), No. 46; and the papers cited *ante*, p. 421.

inorganic origin. Occasionally this dendritic aggregation has taken place within a rock, and, instead of being confined to the fine fissure of a joint, has radiated through the substance of the stone. When the matrix is light in colour, and the oxide, as usual, is dark, remarkable diagram-like effects are produced. The close-grained limestone known as "landscape-marble" owes its peculiarity to this source.[1]

Fig. 220.—Dendritic markings due to the arborescent deposit of earthy oxide of manganese in the close-fitting joint of a fine-grained rock.

**Alternations and Associations of Sediments.**—Though great variations occur in the nature of the strata composing a mass of sedimentary rocks, it may often be observed that certain repetitions occur. Sandstones, for example, are found to be interleaved with shale above, and then to pass into shale; the latter may in turn become sandy at the top and be finally covered by sandstone, or may assume a calcareous character and pass up into limestone. Such alternations bring before us the conditions under which the sedimentation took place. A sandstone group indicates water of comparatively little depth, moved by changing currents, bringing the sand, now from one side, now from another. The passage of such a group into one of shale

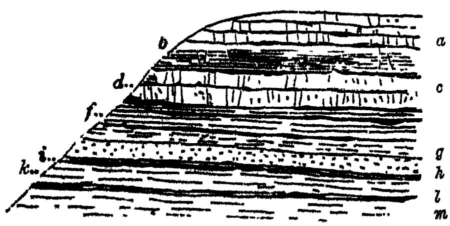



Fig. 221.—Section of strata from the base of the Lias down to the top of the Trias, Shepton Mallet (*B.*). *a*, grey Lias limestone and marls; *b*, earthy whitish limestone and marls; *c*, earthy white limestone; *d*, arenaceous limestone; *f*, grey marls; *g*, red marls; *h*, sandstone with calcareous cement; *i*, blue marl; *k*, red marl; *l*, blue marl; *m*, red marls.

points to a diminution in the motion and transporting power of the water, perhaps to a sinking of the tract, so that only fine mud was intermittently brought into it. The advent of limestone above the shale serves to show that the water cleared, owing to a deflection of the sediment-carrying currents, or to continued and perhaps more rapid subsidence, and

[1] H. B. Woodward, *Geol. Mag.* 1892, p. 110; B. Thompson, *Q. J. G. S.* l. (1894), p. 393.

that foraminifera, corals, crinoids, mollusks or other lime-secreting organisms, established themselves upon the spot. Shale overlying the limestone would tell of fresh inroads of mud, which destroyed the animal life that had been flourishing on the bottom; while a return of sandstone beds would mark how, in the course of time, the original conditions of troubled currents and shifting sandbanks were resumed. Such alternating groups of sandy, calcareous and argillaceous strata are well illustrated among the Jurassic formations of England (Fig. 221).

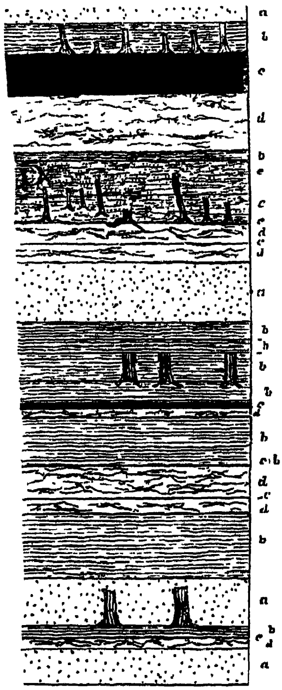


Fig. 222.—Succession of buried coal-growths and erect tree-stumps, Sydney Coal-field, Cape Breton (R. Brown).[2]

*a*, sandstones; *b*, shales; *c*, coal-seams; *d*, beds containing roots and stumps *in situ*.

Certain kinds of strata commonly occur together, because the conditions under which they were formed were apt to arise in succession. One of the most familiar examples is the association of coal and fire-clay. In Britain a seam of coal is generally found to lie on a bed of fire-clay, or on some argillaceous stratum. The reason of this union becomes at once apparent when we recognise the fire-clay as the soil on which the plants grew that went to form the coal. Where the clay was laid down under suitable circumstances, vegetation sprang up upon it. This appears to have taken place in wide shallow lagoon-like expansions of the sea, bordering land clothed with dense vegetation, and to have been accompanied by slow, intermittent, but prolonged subsidence of the sea-bottom. Hence, during pauses of the downward movement, when the water shoaled, an abundant growth of water-loving or marshy plants sprang up on the muddy bottom, somewhat like the mangrove-swamps of the present day, and continued to flourish until the muddy soil was exhausted,[1] or until subsidence recommenced and the matted jungles, carried under the water, were buried under fresh inroads of sand or mud. Each coal-field thus contains a succession of buried forests with a constant repetition of the same kind of intervening strata (Fig. 222).

For obvious reasons, conglomerate and sandstone occur together, rather than conglomerate and shale. The agitation of the water which could form and deposit coarse detritus, like that composing conglomerate, was too great to admit of the accumulation of fine silt. On the other hand, we may look for shale or clay rather than sandstone, as an accompaniment of limestone, inasmuch as when the gentle currents by which fine argillaceous silt was carried in suspension ceased, they would be succeeded by intervals of quiet clearing of the water, during which calcareous material might be elaborated either chemically or by the action of living organisms.

[1] Sterry Hunt has called attention to the fact that the underclays of the Coal-measures have generally been deprived of their alkalies by the vegetable growth which they supported. In the little coal-basins of France evidence has been obtained that much of the coal was formed out of vegetation that had been swept down and buried by rapid currents. See the memoir of M. Fayol cited on p. 635.

[2] R. Brown, *Q. J. G. S.* vi. p. 115; and De la Beche, 'Geol. Observer,' p. 505.

**Relative persistence of Sediments.**—A little reflection will convince the student that all sedimentary rocks must thin out and disappear, and that even the most persistent, when regarded on the great scale, are local and lenticular accumulations. Derived from the degradation of land, they have accumulated near land. They are necessarily thickest in mass, as well as coarsest in texture, nearest to the source of supply, and become more attenuated and fine-grained as they recede from it. We have only to observe what takes place at the present time on lake-bottoms, estuaries, or sea-margins, to be assured that this is now, and must always have been, a law of sedimentation.

But while all sedimentary deposits must be regarded as essentially local, some kinds possess a far greater persistence than others.

As a general rule, it may be said that the coarser the grain, the more local the extent of a rock. Conglomerates are thus by much the most variable and inconstant of all sedimentary formations. They suddenly sink down from a thickness of several hundred feet to a few yards, or die out altogether, to reappear, perhaps farther on, in the same wedge-like fashion. Sandstones are less liable to such extremes of inconstancy, but they too are apt to thin away and to swell out again. Shales are much more persistent, the same zone being often traceable for many miles. Limestones sometimes occur in thick local masses, as among the Silurian formations, but they often also display remarkable continuity. Three thin limestone bands, each of them only a few feet in thickness, and separated by a considerable mass of intervening sandstones and shales, can be traced through the coal-fields of Central Scotland over an area of at least 1000 square miles. Coal-seams, too, possess great persistence. The same seams, varying slightly in thickness and quality, may often be traced throughout the whole of an extensive coal-field.


Fig. 228.—Section to illustrate the great lithological differences of contemporaneous deposits occupying the same horizon.
*a*, conglomerate; *b*, sandstone; *c*, shale; *d d*, limestone.

What is thus true of individual strata may be affirmed also of groups of such strata. A thick mass of sandstone will be found as a rule to be more continuous than one of conglomerate, but less so than one of shale. A series of limestone beds usually stretches farther than either arenaceous or argillaceous sediments. But even to the most extensive stratum or group of strata there must be a limit. It must end off, and give place to others, either suddenly, as a bank of shingle is succeeded by the sheet of sand heaped against its base, or, as is more usual, very gradually, by insensibly passing into other strata on all sides.

Great variations in the character of stratified rocks may frequently be observed in passing from one part of a country to another along the outcrop of the same rocks. Thus, at one end, we may meet with a thick series of sandstones which, traced in a certain direction, may be found passing into shales (Fig. 228). A group of strata may consist of massive conglomerates at one locality, and may graduate into fine fissile flag-stones in another. A thick mass of clay may be found to alternate more and

more with shelly sands as it is traced outward, until it loses its argillaceous nature altogether.

Interesting illustrations of such arrangements occur in the south-west of England, where what are now groups of hills, like the Mendip, Malvern and other eminences, formerly existed as islands in the Mesozoic sea. De la Beche pointed out that the upturned Carboniferous limestone (*a a* in Fig. 224) has formed the shore against which

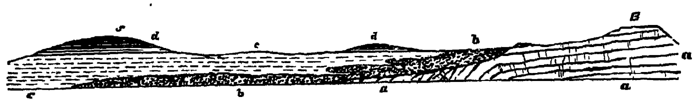


Fig. 224.—Section near Bristol to show how conglomerate may pass into clay along the same horizon. B, Blaize Castle Hill; *s*, Mount Skitham (*B.*).

the coarse shingle of the dolomitic conglomerate (*b b*) accumulated; that the latter, traced away from its shore-line, passes on the same plane into red marl (*c*), and that during a gradual subsidence the clays and limestones of the Lias (*d*) crept over the depressed shore-line. He likewise called attention to the important fact that, in such cases, a continuous zone of conglomerate may belong to many successive horizons. In Fig. 225 a section is given from one of the islands in the south-west of England, round

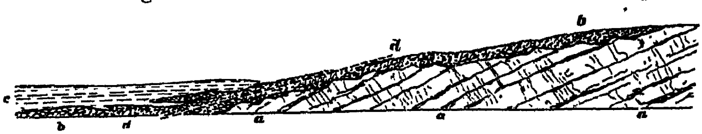


Fig. 225.—Section of part of the flank of the Mendip Hills (*B.*), showing the Carboniferous Limestone (*a a*) overlaid by dolomitic conglomerate (*b b*), and that by red marls (*c*).

which the Trias and Lias were deposited. Denudation has stripped off a portion of the overlying red marls. If the rest of the section to the left of the dotted line (*d d*) were removed, there would remain a continuous mass of conglomerate, which, in default of other evidence to the contrary, would be regarded as one bed laid down upon the sloping surface of limestone, instead of, what it really is, a series of shore gravels piled upon each other, and belonging to a consecutive series of deposits.

Mere difference of lithological character, even within a limited geographical space, does not necessarily mean diversity of age. At the present day, coarse shingle may be formed along the beach, at the same time that the finest mud is being laid down on the same sea-bottom farther from land. The existing differences of character between the deposits of the shore and of the opener sea would no doubt continue to be maintained, with slight geographical displacements, even if the whole area were undergoing subsidence, so that a thick group of littoral deposits might gather in one tract, and of deeper-water accumulations in another.

Among the formations of former geological periods, the same conditions of deposition appear sometimes to have continued for enormous periods. The thick Carboniferous Limestone of Western Europe evidently accumulated during a slow subsidence, when conditions of clear water, with abundant growth of crinoids, corals, mollusks, &c., continued for a period vast enough to admit of the gradual growth of thousands of feet of calcareous matter. Traced northwards into Scotland, this massive limestone is gradually replaced by sandstones, shales, ironstones and coal-seams. These strata prove that the deeper and clearer water of Belgium, Central England, and Ireland passed northwards into muddy flats and sandy shoals, which at one time were overspread with coal-growths, and at another, owing to more rapid subsidence, were depressed beneath the clearer sea which brought with it the organisms whose remains are now to be seen in intercalations of crinoidal limestone.

**Influence of the Attenuation of Strata upon apparent Dip.**—Where a thick mass of sedimentary materials rapidly thins away in a given direction, a deceptive resemblance to the effects of underground movement may be observed. If, for example, we suppose that on a perfectly level bottom a series of sedimentary beds is accumulated at one place to a depth of 5000 feet, and that this series dies out in a distance of 80 miles, the inclination due to this attenuation will amount to a slope of about 62 feet in a mile. That this structure has not been without considerable influence on the apparent dip of stratified rocks has been well shown by W. Topley with reference to the Mesozoic rocks of the south-east of England.[1]

**Overlap.**—Sediment laid down in a subsiding region, wherein the area of deposit is gradually increased, spreads over a progressively augmenting surface. Under such circumstances, the later portions of a formation, or series of sedimentary accumulations, will extend beyond the limits of the older parts, and will repose directly upon the shelving bottom. This relation, called Overlap (Fig. 226), in which the higher

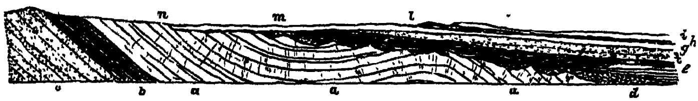



Fig. 226.—Section of Overlap in the Lower Jurassic series of the South-west of England (B.).
The Old Red Sandstone (c), Lower Limestone Shale (b), and Carboniferous Limestone (a) having been previously upraised and denuded, the older beaches (d m), laid down unconformably upon them, were successively covered by conformable Jurassic beds. The Lias (e), with its upper sands (f), is overlapped by the extension of the Inferior Oolite (g) completely across their edges, until this formation comes to rest directly on the Palæozoic strata at n. The corresponding extension of the overlying Fuller's Earth (h l) and limestone (i) has been removed by denudation.[2]

or newer members are said to "overlap" the older, may often be detected among formations of all geological ages. It often brings before us the shore-lines of ancient land-surfaces, and shows how, as these sank under water, the gravels, sands and silts gradually advanced and covered them.

This structure must be carefully distinguished from Unconformability (*postea*, p. 820). In Overlap there is no break in the sequence of formations; the strata that overlap follow on continuously upon those which are overlapped. But in Unconformability there is a break in the succession, the overlying rocks have been laid down on the previously uptilted and denuded edges of those below them. In Fig. 226, for example, the upper or Mesozoic formations (*d* to *i*) form an unbroken series, so do the lower or Palæozoic strata (*a b c*), but the latter have been disturbed and worn down before the deposition of the strata above them. The two series are said therefore to be unconformable.

**Relative Lapse of Time represented by Strata and by the Intervals between them.**—Of the absolute length of time represented by any strata or groups of strata, no satisfactory estimates have yet been possible. Certain general conclusions may indeed be drawn, and comparisons may be made between different series of rocks. Sandstones full of false-

[1] *Q. J. G. S.* xxx. (1874), p. 186. [2] De la Beche, 'Geol. Observer,' p. 485.

bedding were probably accumulated more rapidly than finely laminated shales or clays. It is not uncommon in certain Carboniferous sandstones to find huge sigillarioid and coniferous trunks imbedded in upright or inclined positions. Where, as in Fig. 227, the trees actually grew on the spot where their stems remain, it is evident that the rate of deposit of the sediment which entombed them must have been sufficiently rapid to have allowed a mass of twenty or thirty feet to accumulate before the decay of the wood.

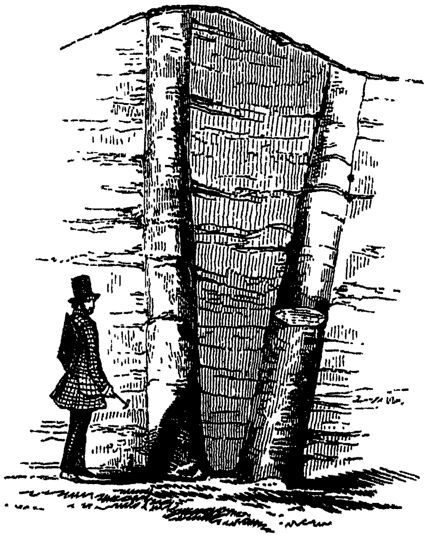


FIG. 227.—Erect trunks of Sigillaria in sandstone, Cwm Llech, head of Swansea Valley, Glamorganshire. (Drawn by W. E. Logan.)

These stems (the largest 5½ feet in circumference) formed part of a series in the same rock, their roots being imbedded in a seam of shale (an old soil) full of fern-leaves, &c. The specimens were removed to the Museum of the Royal Institution of South Wales at Swansea.[1]

Of the durability of these ancient trees we of course know nothing; though modern instances are on record where, under certain circumstances, submerged trees have lasted for some centuries. We may conjecture that where upright or inclined stems are enveloped in one continuous stratum, the rate of accumulation was probably, on the whole, somewhat rapid. The general character of the strata among which such erect tree-trunks occur, obviously indicates shallow-water conditions, with continuous or intermittent subsidence. Unless soon submerged, dead trees would be subject to speedy subaerial decomposition. It occasionally happens that an erect trunk has kept its position even during the accumulation of a series of strata around it (Fig. 228). We can hardly believe that in such cases any considerable number of years could have elapsed between the death of the tree and its final entombment. From the decayed condition of the interior of some imbedded trees, we may likewise infer that accumulation of sediment is not always an extremely slow process. Instances occur where (as Fig. 229), while sand and mud have been accumulating round the submerged stem, its interior has been rotting, so that eventually a mere hollow cylinder has been left, into which sediment and different plants (sometimes with the bodies of land animals) were intro-

[1] De la Beche, 'Geol. Observer,' p. 501.

duced from above.[1] Large coniferous trunks (as in the neighbourhood of Edinburgh) have been imbedded in sandstone, and have had their internal microscopic structure well preserved. In such examples, the drifted trees seem to have sunk with their heavier or root-end touching the bottom, and their upper end pointing upward in the direction of the current, like the snags of the Mississippi, and to have been completely buried in sediment before decay.

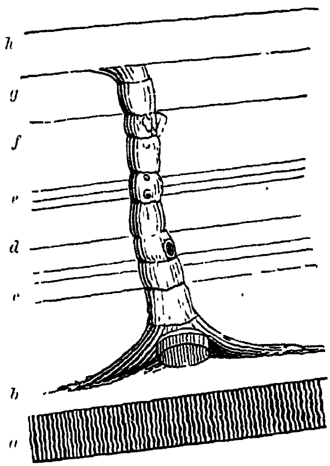



Fig. 228.—Erect tree-trunk rising through a succession of strata, Killingworth Colliery, Newcastle (*B.*).

*a*, High Main Coal-seam; *b*, bituminous shale; *c*, blue shale; *d*, compact sandstone; *e*, shales and sandstones; *f*, white sandstones; *g*, micaceous sandstone; *h*, shale.

Continuous layers of the same kind of deposit suggest a persistence of geological conditions; numerous alternations of different kinds of sedimentary matter point to vicissitudes or alternations of conditions. As a rule, we should infer that the time represented by a given thickness of similar strata was less than that shown by the same thickness of dissimilar strata, because the changes needed to bring new varieties of sediment into the area of deposit would usually require the lapse of some time for their completion. But this conclusion might often be erroneous. It would be best supported when, from the very nature of the rocks, wide variations in the character of the water-bottom could be established. Thus a group of shales followed by a fossiliferous limestone would mark a period of slow deposit and quiescence, almost always of longer duration than would be indicated by an equal depth of sandy strata, pointing to more active sedimentation. Thick limestones, made up of remains of organisms which lived and died upon the spot, and whose remains are crowded together, generation above generation, must have demanded prolonged periods for their formation.

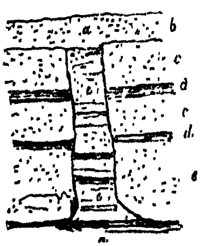



Fig. 229.—Erect tree-trunk (*a a*) imbedded in sandstones (*c c*) and shales (*d d*), its interior filled with different sandy and clayey strata (*e e*), and the whole covered by a sandstone bed (*b*) (*B.*)

But in all speculations of this kind, we must bear in mind that the relative length of time represented by a given depth of strata is not to be estimated merely from thickness or lithological characters. It has already been pointed out that the interval between the deposit of two successive laminæ of shale may have been as long as, or even longer than, that required for the formation of one of the laminæ. In like manner, the interval needed for the transition from one stratum or kind of strata to another may often have been more than equal to the time required for the formation of the strata of either kind. But the relative chronological importance of the bars or lines in the geological record can seldom be satisfactorily discussed merely on lithological grounds. This must mainly be decided on the evidence of organic remains, as will be shown in Book V. By this kind of evidence, it can be made nearly certain that the intervals represented by strata were in many cases much shorter than those not so represented,—in other words, that the time

[1] The hollow tree-trunks of the Nova Scotian coal-fields have yielded a most interesting series of terrestrial organisms—land-snails and reptiles. For illustrations of trees in Coal-measure strata and the deposition of sediment round them, see the Atlas to M. Fayol's memoir cited on p. 635.

during which no deposit of sediment went on at any particular locality was longer than that wherein deposit did take place.

**Ternary Succession of Sediments.**—In following the order of sedimentation among the stratified rocks of the earth's crust, the observer will be led to remark a more or less distinct threefold arrangement or succession in which the sandy, muddy and calcareous sediments have followed each other. Phillips and E. Hull have called attention to this structure, illustrating it by reference to the geological formations of Great Britain; while Newberry, Sterry Hunt and J. W. Dawson have discussed it in relation to the stratigraphical series of North America. According to Professor Hull, a natural cycle of sedimentation consists of three phases: 1st, a lower stage of sandstones, shales and other sedimentary deposits, representing prevalence of land with downward movement; 2nd, a middle stage, chiefly of limestone, representing prevalence of sea with general quiescence and elaboration of calcareous organic formations; 3rd, an upper stage, once more of mechanical sediments indicative of proximity to land.[1]

Where the strata are interrupted by disturbance and unconformability, we may suppose the cycle of sedimentation to have been completed by upheaval after prolonged subsidence. But where the continuity of the formations is unbroken, as it is over such vast tracts in North America, upheaval is not required, and the facts seem explicable, as Phillips long ago showed, on the idea of prolonged but intermittent subsidence. Let us suppose a downward movement to commence, and to depress successive sheets of gravel, shingle, sand and other shallow-water accumulations, derived from the erosion of neighbouring land. If the depression be comparatively rapid, the bottom may soon be carried beyond the reach of at least the coarser kinds of sediment, and marine lime-secreting organisms may afterwards begin to form a calcareous floor beneath the sea. Let us imagine further, that the subsidence ceases for a time, and that by the accumulation of organic remains, and partly also by the deposit of fine muddy sediment, the water is shallowed. With this gradual change of depth, the coarser detritus begins once more to be able to stretch seawards, and to overspread the limestones, which, under the altered circumstances, cease to be formed. A gradual silting up of the area takes place, marked by beds of sand and mud, until a renewal of the subsidence, either suddenly or slowly, restores the previous depth and clearness of water, and allows either the old marine organisms, which had been driven off, or their modified descendants to re-occupy the area and build new limestone.

**Groups of Sedimentary Strata.**—Passing from individual strata to masses of stratified rock, the geologist finds it needful for convenience of reference to subdivide these into groups. He avails himself of two bases of classification—(1) lithological character, and (2) organic remains.

1. The subdivision of stratified rocks into groups according to their mineral aspect is an obvious and easily applied classification. Moreover, it often serves to connect together rocks formed continuously in certain circumstances which differed from those under which the strata above and

[1] Phillips, *Mem. Geol. Surv.* ii.; 'Geol. Yorkshire,' ii.; 'Geol. Oxford,' p. 293; Hull, *Quart. Jour. Sci.* July 1869; Newberry, *Proc. Amer. Assoc.* 1873, p. 185; *Proc. Lyceum Nat. Hist. New York*, 2nd ser. No. 4, p. 122; Hunt, in Logan's 'Geology of Canada,' 1863, p. 627; *Amer. Journ. Sci.* (2nd series), xxxv. p. 167; Dawson, *Q. J. G. S.* xxii. p. 102; 'Acadian Geology,' p. 135. Compare on this subject E. van den Broeck, *Bull. Mus. Roy. Bruxelles*, ii. (1883), p. 341; A. Rutot, *op. cit.* p. 41.

below were laid down—so that it expresses natural and original subdivisions of strata. In the middle of the English Carboniferous system of rocks, for example, a zone of sandy and pebbly beds occurs, known as the Millstone Grit. No abrupt and sharp line can be drawn between these strata and those above and below them. They shade upward and downward into the beds between which they lie. Yet they form a conspicuous belt, traceable for many miles by the scenery to which it gives rise.

Again, the red rocks of Central England, with their red sandstones, marls, rock-salt and gypsum, form a well-marked group, or rather series of groups. It is obvious, however, that characters of this kind, though sometimes wonderfully persistent over wide tracts of country, must be at best but local. The physical conditions of deposit must always have been limited in extent. A group of strata, showing great thickness in one region, will be found to die away as it is traced into another. Or its place is gradually taken by another group which, even if geologically contemporaneous, possesses totally different lithological characters. Just as at the present time a group of sandy deposits gradually gives place along the sea-floor to others of mud, and these to others of shells or of gravel, so in former geological periods, contemporaneous deposits were not always lithologically similar. Hence mere resemblance in mineral aspect cannot usually be regarded as satisfactory evidence of contemporaneity, except within comparatively contracted areas. The Carboniferous Limestone has already (p. 652) been cited as a notable example. Typically in Belgium, Central England and Ireland, it is a thick calcareous group of rocks, full of corals, crinoids and other organisms, which bear witness to the formation of these rocks in the open sea. But traced into the north of England and Scotland, it passes into sandstones and shales, with numerous coal-seams, and only a few thin beds of limestone. The soft clay beneath the city of London is represented in the Alps by hard schists and contorted limestones. We conclude, therefore, that lithological agreement, when pushed too far, is apt to mislead us, partly because contemporaneous strata often vary greatly in lithological character, and partly because the same lithological characters may appear again and again in different ages. By trusting too implicitly to this kind of evidence, we may be led to class together rocks belonging to very different geological periods, and, on the other hand, to separate groups which really, in spite of their seeming distinction, were formed contemporaneously.

2. It is by the remains of plants and animals imbedded among the stratified rocks that the most satisfactory subdivisions of the geological record can be made, as will be more fully stated in Books V. and VI. A chronological succession of organic forms can be made out among the rocks of the earth's crust. A certain common facies or type of fossils is found to characterise particular groups of rocks, and to hold true even though the lithological constitution of the strata should greatly vary. Moreover, though comparatively few species are universally diffused, some possess remarkable persistence over wide areas; and even when they are replaced by others, the same general facies of fossils remains. Hence the stratified formations of two countries geographically distant, and having little or no lithological resemblance to each other, may be compared and paralleled simply by means of their enclosed organic remains.

**Order of Superposition—the Foundation of Geological Chronology.**—As sedimentary strata were laid down upon one another in a more or less nearly horizontal position, the underlying beds must be older than those which cover them. This simple and obvious truth is termed the Law of Superposition. It furnishes the means of determining the

chronology of rocks; and though other methods of ascertaining this point are employed, they must all be based originally upon the observed order of superposition. The only case in which the apparent superposition may be deceptive is when the strata have been inverted, as in the Alps (pp. 676, 693), where the rocks composing huge mountain masses have been so completely overturned that the highest beds appear as if regularly covered by others which ought properly to underlie them. But these are exceptional occurrences, wherein the true order can usually be made out from other sources of evidence.

## PART II. JOINTS.

All rocks are traversed more or less distinctly by vertical or highly inclined divisional planes termed Joints.[1] Soft rocks, indeed, such as

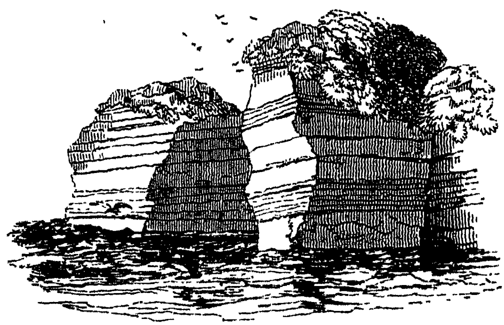


Fig. 230.—Cliffs cut into re-entering angles by lines of Joint (*B.*).
(The faces in shadow are one set of joints, those in light another set.)

loose sand and uncompacted clay, do not show these lines; but where a sedimentary mass has acquired some degree of consolidation, it usually displays them more or less distinctly. It is by means of the intersection of joints that rocks can be removed in blocks; the art of quarrying consists in taking advantage of these natural planes of division. As joints differ somewhat in character according to the nature of the material which they

[1] Professor Daubrée proposed a classification of the various divisional planes of rocks due to rupture of original continuity, which he grouped together as *Lithoclases*. 1. Under the term *Leptoclase* he classed minor fractures, which may be either (*a*) *synclases*, produced by some internal mechanical or molecular action, and generally by contraction, as in cooling and drying; or (*b*) *piësoclases*, produced by some external mechanical movement, particularly by pressure, as in the structures called cone-in-cone, stylolites, and ruiniform marble. 2. *Diaclases* correspond to what in English are called joints. 3. *Paraclases* are faults. *Bull. Soc. Géol. France* (3), x. p. 136. On jointing, faulting and cleavage in rocks, see O. Fisher, *Geol. Mag.* 1884, p. 204. A. Harker, *Geol. Mag.* 1885, *Brit. Assoc.* 1885, p. 813. G. K. Gilbert, *Amer. Journ. Sci.* xxiii. (1882), p. 25; xxiv. (1882), p. 50; xxvii. (1884), p. 47. W. O. Crosby, *Proc. Boston Soc. Nat. Hist.* xxii. (1882), p. 72; xxiii. p. 243. *Amer. Geol.* xii. (1893), p. 368. J. B. Woodworth, *Proc. Boston Soc. Nat. Hist.* xxvii. (1896), p. 163. G. F. Becker, *Bull. Geol. Soc. Amer.* iv. (1893), pp. 41-75; *Trans. Amer. Inst. Min. Engin.* xxiv. (1894), p. 130. C. R. Van Hise, *Journ. Geol.* iv. (1896), p. 609.

traverse, we may consider them in reference to the three great classes of rocks.

1. **In Stratified Rocks.**—To the presence of joints some of the most familiar features of rock-scenery are due (Fig. 230). Joints vary in the angles at which they cut the planes of bedding, in the sharpness of their definition, in the regularity of their perpendicular and horizontal course, in their lateral persistence, in number, and in the directions of their intersection. As a rule, they are most sharply defined in proportion to the fineness of grain of the rock. In limestones and close-grained shales, for example, they often occur so clean-cut as to be invisible until revealed by fracture, or by the slow disintegrating effects of the weather. The rock splits up along these concealed lines of division, whether the agent of

Fig. 231.—Jointing in quarry of Caithness Flags, near Holburn Head.

demolition be the hammer or frost. In coarse-textured rocks, on the other hand, joints are apt to show themselves as more irregular sinuous rents. Occasionally one series of joints is so close-set as to divide the rocks into thin parallel plates, and to give a new fissility much more pronounced than that of the bedding planes.

As a rule, joints run perpendicular, or approximately so, to the planes of bedding, and descend vertically at not very unequal distances, so that the portions of rock between them, when seen in profile, appear marked off into so many wall-like masses. But this symmetry often gives place to a more or less tortuous course, with lateral joints in various random directions, more especially where the different strata vary considerably in lithological characters. A single joint may be traced for many yards, sometimes, it is said, for several miles, more particularly when the rock is fine-grained, as in limestone. But where the texture is coarse and unequal, the joints, though abundant, run into each other, in such a way that no one in particular can be identified for more than a limited distance. The number of joints in a mass of stratified rock varies within wide limits. Among strata which have undergone little disturbance, the joints may be separated from each other by intervals of several yards. But in other cases where

terrestrial movement has been considerable, the rocks are so jointed as to have acquired therefrom a fissile character that has nearly or wholly obliterated their tendency to split along the lines of bedding.

An important feature in the joints of stratified rocks is the direction in which they intersect each other. In general they have two dominant trends, one coincident, on the whole, with the direction in which the strata are inclined from the horizon, and the other running transversely at a right angle or nearly so. The former set is known as *dip-joints*, because they run with the *dip* or inclination of the rocks; the latter is termed *strike-joints*, inasmuch as they conform to the *strike* or general outcrop. It is owing to the existence of this double series of joints that ordinary quarrying operations can be carried on. Large quadrangular blocks can be wedged off, which would be shattered if exposed to the risk of blasting. A quarry is usually worked to the dip of a

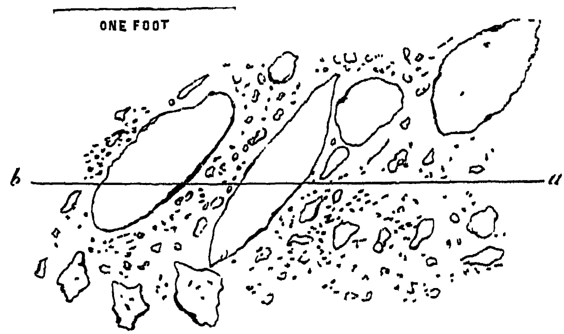



Fig. 232.—Plan of coarse conglomerate of blocks of Cambrian rocks in Carboniferous Limestone, traversed by a line of joint cutting the individual boulders in the line *a b*. Coast near Skerries, Dublin County (*B.*).

rock; hence the strike-joints form clean-cut faces in front of the workmen as they advance. These are known as "backs," and the dip-joints, which traverse them, as "cutters." The way in which this double set of joints occurs in a quarry may be seen in Fig. 231, where the close parallel lines traversing the shaded and unshaded faces mark the planes of stratification, which here are inclined from the spectator. The steep faces in light are defined by the strike-joints or "backs." The faces in shadow have been quarried out along dip-joints or "cutters." It will be observed that the long face in sunlight is cut by parallel lines of dip-joints not yet opened in quarrying; while in like manner, the shaded face to the right is that of a dip-joint which is traversed by parallel lines of strike-joint.

Ordinary household coal presents a remarkably well-developed system of joints. A block of such coal may be observed to be traversed by fine laminæ, the surfaces of many of which are soft and soil the fingers. These are the planes of stratification. Perpendicular to them run divisional planes, which cut each other at right angles or nearly so, and thus divide the mineral into cubical fragments. One of these sets of joints makes clean sharply defined surfaces, and is called by English miners the *face*, *slyne*, *cleat* or *bord;* the other has rougher, less regular surfaces, and is known as the *end*. The face remains persistent over wide areas; it serves to define the direction of the roadways in coal-mines, which must run with it.

According to observations made by Jukes, both strike-joints and dip-joints occur in beds of recently formed coral-rock in the Australian and other reefs.[1] In like manner, a remarkably definite system of jointing has been noticed by Mr. Gilbert in the recent

[1] 'Manual of Geology,' 3rd edition, p. 184.

clays and muds of the dried-up bed of the Sevier lake in Utah. Such modern sedin have certainly never been subject to the pressure of any superincumbent rock, n the torsion or other disturbance incident to subterranean movement. That great has sometimes been concerned in the production of the structure is instructively sl in some conglomerates, where the joints traverse the enclosed pebbles, as well as surrounding matrix, in such a way that large blocks of hard quartz are cut throug them as sharply as if they had been sliced in a lapidary's machine, and the same j can be traced continuously through many yards of the rock (Fig. 232).[1] Indicati relative movement of the sides of a joint is often supplied by their rubbed and str surfaces, termed *slickensides*, which have evidently been ground against each o They are often coated with hæmatite, calcite, chlorite or other mineral, which taken a cast of the striæ and then seems itself to be striated.

**Origin of Joints.**—Probably more than one natural process been concerned in the production of joints, though the several ca cannot be always satisfactorily discriminated in the effects. Two r sources of these divisional rents are obviously (1) Tension, where rocks have been pulled in two opposite directions, and (2) Torsion, w they have been driven together, and especially where they have l subjected to the strain of torsion.

(1) *Tension.*—The contraction of rocks gives rise to fissures of retreat in their whether it results from the drying and consolidation of aqueous sediments or fro cooling of masses that have been molten or have been highly heated. The prisma columnar system of joints observable in the gypsum of the Paris Basin, the be which are divided from top to bottom into vertical hexagonal prisms, may be an ins of this cause.[2] A columnar structure has often been superinduced upon stratified (sandstone, shale, coal) by contact with intrusive igneous masses (p. 769). V strata are thrown into arches and troughs, they necessarily undergo considerable te along the axis of the folds, and when the stress exceeds their elastic limit they o relief by rupture, probably sometimes in the form of innumerable longitudinal j sometimes of lines of fault. This cause, however, would give rise mainly to one joints parallel to the strike of the rocks.

(2) *Torsion.*—In experiments on the behaviour of various substances under the s of torsion, Daubrée produced two groups of cracks oblique to the axis of torsion, cr each other at large angles, and having a striking resemblance to the normal inters joints which occur among stratified rocks. He concluded that a system of joints be explained as the results of the torsion of strata arising during the moveme which the crust of the earth has been subjected.[3]

Mr. W. O. Crosby in 1882 proposed the explanation that the most abundant ty joints, that of the straight, parallel and intersecting system, arise as the results c earth-waves generated during earthquakes, the rocks through which the waves being exposed to such powerful alternate compression and tension as to rupture th

Joints form natural lines for the passage downward and upwar subterranean water (p. 465). They likewise furnish an effective lodg for the action of frost, which wedges off blocks of rock in the ma already described (p. 532). As they serve, in conjunction with beddin divide stratified rocks into large quadrangular blocks, their influence i

[1] De la Beche, 'Geol. Observer,' p. 628.

[2] Jukes's 'Manual,' 3rd edition, p. 180.

[3] 'Études de Géologie expérimentale,' p. 300 ; and *ante*, p. 423. His experiments been repeated by G. F. Becker, *Trans. Amer. Inst. Min. Engin.* xxiv. (1894), p. 130.

[4] W. O. Crosby, papers cited p. 658.

weathering of these rocks is seen in the symmetrical and architectural as well as the splintered and dislocated aspects so familiar in the scenery of sandstone and limestone districts.

2. **In Igneous (Massive) Rocks.**—While in stratified rocks, the divisional planes consist of lines of bedding and of joint, cutting each

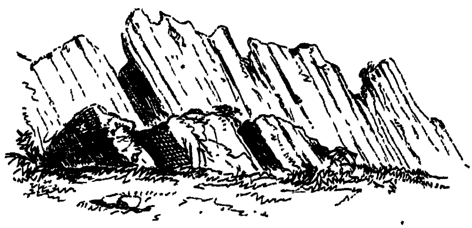


Fig. 233.—Porphyry, near Clynog Vawr, Caernarvonshire, divided into slabs by a system of close parallel joints (*B.*).

other usually at a high, if not a right angle; in igneous (massive) rocks, they include joints only; and as these do not, as a rule, present the same parallelism as lines of bedding, unstratified rocks, even though as full of joints, have not the regularity of arrangement of stratified formations. Some massive rocks indeed may have one system of divisional planes so largely developed as to acquire a bedded or fissile character. This structure, characteristically shown by some phonolites, may also be detected among ancient porphyries (Fig. 233). Most massive rocks are traversed by two intersecting sets of chief or "master" joints, whereby the rock is

Fig. 234.—Jointed structure of Granite.

divided into long quadrangular, rhomboidal, hexagonal, or polygonal columns. The most perfect examples of columnar or prismatic jointing are to be found in rocks of the basalt family. A third set of joints may usually be noticed cutting across the columns and articulating them into segments, though generally less continuous and dominant than the others (Fig. 234). When these last-named cross-joints are absent or feebly developed, columns many feet in length can be quarried out entire. Such monoliths have been from early times employed in the construction of obelisks and pillars.

In large masses of granite, an outward inclination of the natural divisional planes of the rock may sometimes be observed, as if the granite were really a rudely bedded mass, having a dip towards and under the strata which rest upon its flanks. It is not a foliated arrangement of the constituent minerals analogous to the foliation of gneiss, for it can be traced in perfectly amorphous and thoroughly crystalline granite, but is undoubtedly a form of jointing by reason of which the rock weathers into large blocks piled one upon another like a kind of rude cyclopean masonry.[1] In the quarrying of granite, the workmen recognise that the rock splits into blocks much more easily in one direction, though externally there is no trace of any structure which could give rise to this tendency.

Rocks of finer grain than granite, such as many diorites and dolerites, acquire a prismatic structure from the number and intersection of perpendicular joints. The prisms, however, are unequal in dimensions, as well as in the number and proportions of their sides, a frequent diameter being 2 or 3 feet, though they may sometimes be observed three times thicker, and extending up the face of a cliff for 300 or 400 feet. It is by means of joints that precipitous faces of crystalline, no less than of sedimentary rock, are produced and maintained, for they serve as openings into which frost drives every year its wedges of ice. They likewise give rise to the formation of the fantastic pinnacles and fretted buttresses characteristic of igneous rocks.

As lava, erupted to the surface, cools and passes into the solid condition, a contraction of its mass takes place. This diminution of bulk is accompanied by the development of divisional planes or joints, more especially diverging from the upper and under surfaces, and intersecting at irregular distances, so as to divide the rock into rude prisms. Occasionally another series of joints, at a right angle to these, traverses the mass, parallel with its upper and under surfaces, and thus the rock acquires a kind of fissile or bedded appearance. The most characteristic structure, however, among volcanic rocks is the prismatic, or, as it is incorrectly termed, "basaltic." Where this arrangement occurs, as it so commonly does in basalt, the mass is divided into tolerably regular pentagonal, hexagonal or irregularly polygonal prisms or columns, set close together at a right angle to the main cooling surfaces (Fig. 235). These prisms vary from 1 inch or even less to 18 or more inches in diameter, and range up to 100 or even 150 feet in height. Many excellent and well-known examples of columnar structure are exhibited on the coast-cliffs of the Tertiary volcanic region of Antrim and the west of Scotland, as in the Giant's Causeway and Fingal's Cave. In many cases, no sharp line can be drawn between a columnar basalt and the beds above and below, which show no similar structure, but into which the prismatic mass seems to pass.

Considerable discussion has arisen as to the mode in which this columnar structure has been produced. That it is a species of jointing, due to contraction, was long ago pointed out by Scrope, and is now generally conceded, though the conditions under which it is produced are not quite clear.[2] Professor James Thomson showed how the columnar structure might be explained as a phenomenon of contraction, and subsequently Mr. Mallet concluded that "all the salient phenomena of the prismatic and jointed structure of basalt can be accounted for upon the admitted laws of cooling, and contraction thereby, of melted rock possessing the known properties of basalt, the essential conditions being a very general homogeneity in the mass cooling, and that the cooling shall take place slowly, principally from one or more of its surfaces." In the more perfectly columnar basalts, the columns are sometimes articulated, each prism

[1] In the granite of the axes of the Rocky Mountains and parallel ranges to the westward, a kind of bedded structure has been described as passing under the crystalline schists.

[2] G. P. Scrope, 'Geology and Extinct Volcanoes of Central France,' p. 92. J. Thomson, *Brit. Assoc.* 1863, Sects. p. 95. R. Mallet, *Proc. Roy. Soc.* 1875 ; *Phil. Mag.* ser. 4, vol. i. pp. 122, 201. T. G. Bonney, *Q. J. G. S.* 1876, p. 140. J. Walther, *Jahrb. Geol. Reichsanst.* 1886, p. 295. J. P. Iddings, *Amer. Journ. Sci.* xxxi. (1886), p. 321.

being separable into vertebræ, with a cup-and-ball socket at each articulation (Figs. 236 and 237). This peculiarity was traced by Mr. Mallet to the contraction of each prism in its length and in its diameter, and to the consequent production of transverse joints, which, as the resultant of the two contracting strains, are oblique to the sides of the prism, but, as the obliquity lessens towards the centre, necessarily assume, when perfect, a cup-shape, the convex surface pointing in the same direction as that in which the prism has grown. This explanation, however, will hardly account for cases, which are not uncommon, where the convexity points the other way, or where it is sometimes in one direction and sometimes in the other.[1] The remarkable spheroids (Fig. 94, p. 456) which appear in many weathered igneous rocks besides basalts may be due, where they are not the result of weathering, to continued contraction within the hexagonal or polygonal spaces defined by the columnar joints and cross-joints of a cooling mass. The contraction of these blocks would tend to the development of successive spheroidal shells, which might remain mutually adherent and invisible in a fresh fracture of the rock, yet might make their presence effective during the complex processes of weathering.[2] After some exposure, the spheroids of basalt begin to appear, and gradually crumble away by the successive formation and disappearance of external weathered crusts or coats,

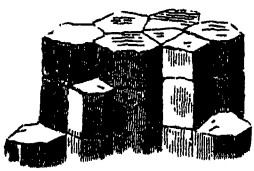


Fig. 235.—Ordinary columnar structure of Lava.

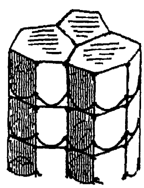


Fig. 236.—Ball-and-socket Jointing of columns.

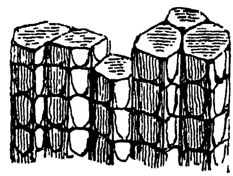


Fig. 237.—Modification of ball-and-socket structure.

which fall off into sand and clay. Almost all augitic or hornblendic rocks, with many granites and porphyries, exhibit the tendency to decompose into rounded spheroidal blocks. The columnar structure, though abundant among modern volcanic rocks, is by no means confined to these. It is as well displayed among the lavas of the Lower Old Red Sandstone, and of the Carboniferous Limestone in Central Scotland, as among those of Tertiary age in Auvergne or the Vivarais.

As already stated, prismatic forms have been superinduced upon rocks by a high temperature and subsequent cooling, as where coal and sandstone have been invaded by basalt. They may likewise be observed to arise during the consolidation of a substance from aqueous solution. In starch, for example, the columnar structure may be well developed, and not infrequently radiates from certain centres, as in basalt and other igneous rocks.

3. **In Foliated (Schistose) Rocks.**—The schists likewise possess their joints, which approximate in character to those among the massive igneous rocks, but they are on the whole less distinct and continuous, while their effect in dividing the rocks into oblong masses is considerably modified by the transverse lines of foliation. These lines play somewhat the same

[1] Scrope pointed this clearly out (*Geol. Mag.* September 1875), though Mallet (*ibid.* November 1875) replied that in such cases the articulations must be formed just about the dividing surface, between the part of the rock which cooled from above and that which cooled from below. See also on this subject J. P. O'Reilly, *Trans. Roy. Irish Acad.* xxvi. (1879), p. 641.

[2] Bonney, *Q. J. G. S.* 1876, p. 151. The perlitic structure is probably a microscopic example of the same kind of contraction.

part as those of stratification among the stratified rocks, though with less definiteness and precision. The jointing of the more massive foliated rocks, such as the coarser varieties of gneiss, approaches most closely to that of granite; in the finely fissile schists, on the other hand, it is rather linked with that of sedimentary formations. Upon these differences much of the characteristic variety of outline presented by cliffs and crests of foliated rocks depends.

**Sandstone Dykes.**—Reference may perhaps be most conveniently made here to the filling up of opened joints or fissures with sedimentary material, so as to give rise to dyke-like veins traversing indifferently any kind of rock. In some cases the origin of these veins is obviously due to the ordinary deposit of sediment over an uneven and rifted surface of submerged land. If such a surface has been worn by denudation into deep clefts and narrow chinks and is then in that condition carried down beneath sea-level, these depressions will be speedily filled up with gravel, sand or silt. On long subsequent re-exposure at the surface, the older rock may be laid bare with numerous pipes or veins of conglomerate or sandstone descending into its mass. Good illustrations of this structure may be seen on the south-western flanks of the mountain Slioch, above Loch Maree, Ross-shire (Fig. 238), where ramifying clefts in the denuded surface of the ancient Lewisian land have preserved the sediments of the Torridonian waters under which that land was submerged.

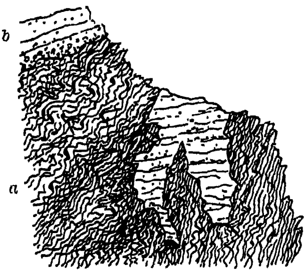



Fig. 238.—Narrow rifts or cracks in the Lewisian gneiss (*a*) filled with Torridonian Conglomerate and Sandstone (*b*), north of Fasach Burn, Kinlochewe, Ross-shire.[1]

But many instances have been observed where the explanation is not so obvious; where the fissures have not been laid bare by denudation, but have been opened by underground movements and have immediately or speedily been filled with sedimentary material. Probably in most cases the infilling has been from above, but in some examples it appears to have come from below. The following illustrations will show the nature and wide distribution of this structure.

Lava-streams in cooling not infrequently split open in irregular fissures. Into these cavities dust and debris may be blown by wind or washed by rain. Where the molten rock has entered a lake or the sea, sandy silt may be washed into the rents and gradually fill them up. This sediment may even be stratified horizontally between the vertical walls of its enclosing fissure. Numerous examples of this structure have been observed among the andesites and other lavas of the Old Red Sandstone of Central Scotland (Fig. 336).

[1] The depth of this fissure is about 3 feet. Mr. C. T. Clough has traced another example in the same district for a length of 2 miles, sometimes descending 100 feet down into the gneiss. Mr. E. Greenly has described a group of sandstone pipes in Anglesey, one of which descends 12 feet from an overlying sandstone into a limestone. *Geol. Mag.* 1900, p. 20.

Professor Pavlow has described some dykes of hard fossiliferous sandstone that traverse the Neocomian clays of the district of Alatyr, Russia. As these clays are soft, fissures opened in them must soon have closed unless rapidly filled with foreign material. Fortunately this material has enclosed contemporaneous organisms which prove it to be a sand of Oligocene age. It would thus appear that the Neocomian clays lay beneath an older Tertiary sea, that they were rent open, probably by a submarine earthquake,

Fig. 289.—Group of Sandstone Dykes in Cretaceous strata on North Fork of Cottonwood Creek, Sacramento Valley, California. Photograph by J. S. Diller, U. S. Geol. Surv. The largest dyke is four inches thick.

and that the fissures thus produced were at once filled up with the sand and shells of the overlying sea-floor. These "sandstone-dykes" become in this way natural seismographs.[1]

Mr. Whitman Cross has described, from the Pikes Peak region of Colorado, a much more ancient series of dykes which traverse a pre-Cambrian granite. They consist of fine even-grained sandstone or quartzite, which has filled a network of nearly parallel fissures with many branches and connecting arms. The veins vary from thin

[1] A. P. Pavlow, *Geol. Mag.* 1896, p. 49.

films up to a few feet in breadth, but some attain a width of many yards, while two form prominent ridges on the surface, with a width of from 200 to 300 yards each. The largest examples can be followed for nearly a mile. These veins have more recently been examined by Mr. W. O. Crosby, who has traced them for many miles along the ground traversed by the great fault of Ute Pass. He has found them closely accompanying this dislocation, and nowhere more than 500 to 1000 feet distant from the principal line of displacement, and he suggests that the fissures were formed at the time of the production of the fault, and were filled in with sand from the overlying Potsdam sandstone.[1]

Sandstone dykes have been met with in some number in Northern California, and under conditions which have suggested another explanation of their origin. Mr. J. S. Diller, who first called attention to them in that region, found forty-five examples there, all approximately parallel, usually vertical, and varying from mere films to eight feet in breadth and from 200 yards to 9½ miles in length (Fig. 239). They consist of an impure quartzose sandstone, and intersect the Cretaceous sandstones and shales along lines of joint, without distortion or displacement of the strata. Mr. Diller has suggested that they represent fissures caused by earthquakes, which have been filled in with sand rapidly injected from below, probably from an underlying sandstone, the material of which resembles that of the dykes.[2]

## Part III. Inclination of Rocks.

The most casual observation is sufficient to satisfy us that the rocks now visible at the earth's surface are seldom in their original position. We meet with sandstones and conglomerates composed of water-worn particles, yet forming the angular scarps of lofty mountains; shales and clays full of remains of fresh-water shells and land-plants, yet covered by limestones made up of marine organisms, and these limestones rising into great ranges of hills, or undulating into fertile valleys, and passing under the streets of busy towns. Such facts, now familiar to every reader, and even to many observers who know little or nothing of systematic geology, point unmistakably to the conclusion that most of the rocks of the land have been formed under water, sometimes in lakes, more frequently in the sea, and that they have been elevated into land.

But further examination discloses other and not less convincing evidence of movement. Judging from what takes place at the present time on the bottoms of lakes and of the sea, we confidently infer that when the strata now constituting so much of the solid framework of the land were formed, they were laid down nearly horizontally, or at least at low angles (*ante*, p. 636). When, therefore, we find them inclined at all angles, and even standing on end, we conclude that they have been disturbed. Over wide spaces, they have been upraised bodily, with little alteration of horizontality; but in most places some departure from that original position has been effected.

**Dip.**—The inclination thus given to rocks is termed their Dip. Its

[1] W. Cross, *Bull. Geol. Soc. Amer.* v. (1894), p. 225; W. O. Crosby, *Bull. Essex Institute, Mass.* xxvii. (1895), p. 113.

[2] *Bull. Geol. Soc. Amer.* i. (1890), p. 411. Mr. Diller refers to earlier notices of the structure by Darwin in California, J. D. Dana in Oregon, Whitney in California, and M'Gee in Eastern Central Mississippi. Mr. Hay has described some instances from Nebraska, *op. cit.* iii. (1892), p. 56.

amount is expressed in degrees measured from the plane of the horizon. Thus a set of rocks half-way between the horizontal and vertical position would be said to dip at an angle of 45°, while if vertical they would be marked with the angle of 90°. The inclination is measured with an instrument termed the Clinometer, which is variously made, but of which

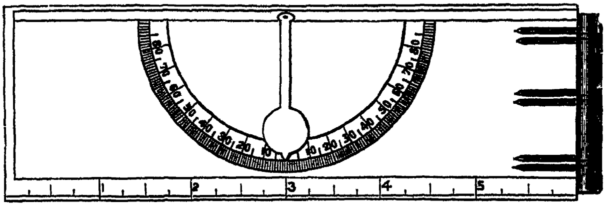


Fig. 240.—Clinometer—the leaf containing the pendulum and index. (Half the size of the original.)

one of the simplest forms is shown in Fig. 240. This consists of a thin strip of boxwood, two inches broad, strengthened with brass along the edges, and divided into two leaves, each 6 inches long, hinged together so that when opened out they form a foot-rule. On the inside of one of these leaves a graduated arc with a pendulum is inserted. When the instrument is held horizontally, the pendulum points to zero. When placed vertically, it marks 90°. By retiring at a right angle to the direction of dip of a group of inclined beds, and holding the clinometer

Fig. 241.—Apparently horizontal Strata (*B.*).

before the eye until its upper edge coincides with the line of bedding, we readily obtain the amount or angle of dip. In observations of this nature it is of course necessary either to place the clinometer strictly parallel with the direction of dip, or, if this be impossible, to take two measurements, and calculate from them the true angle.[1] Simple as observation of dip is, it is attended with some liabilities to error, against which the

[1] In Jukes's "Memoir on the South Staffordshire Coal-field," in *Memoirs of Geol. Survey* (2nd edit. p. 213), a formula is given for calculating the true dip from the apparent dip seen in a cliff. A graphical method of computing the true dip from observations of two apparent dips has been suggested by Mr. W. H. Dalton, *Geol. Mag.* x. p. 332. See also Green's 'Physical Geology,' 1882, p. 460. A. Harker, *Geol. Mag.* 1884, p. 154, and a paper on the use of the protractor in field-geology, *Proc. Roy. Dublin Soc.* viii. (1896), p. 12.

observer should be on his guard. A single face of rock may not disclose the true dip, especially if it be a clean-cut joint-face. In Fig. 241, for example, the strata might be supposed to be horizontal; but another side view of them (as Fig. 242) might show them to be gently inclined or even nearly vertical.

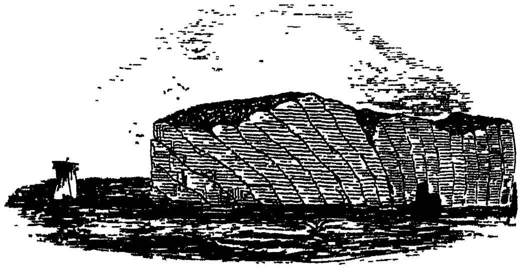


Fig. 242.—Real inclination of Strata shown in Fig. 241 (*B.*).

Again, a deceptive surface inclination is not infrequently to be seen among thin-bedded strata. Mere gravitation, aided by the downward pressure of sliding detritus or "soil-cap," suffices to bend over the edges of fissile strata, which, though really dipping into the hill, are thus made to appear superficially to dip away from it (Fig. 243). Similar effects, with even proofs of contortion, may be noticed under boulder-clay, or in other situations where the rocks have been bent over and crushed by a mass of ice.

When the dip is outward in every direction from a central point, it is said to be *quâ-quâ-versal* (A in Fig. 245). Strata thus affected are thrown into a dome-shaped structure; while when the dip is towards a central point, they have a basin-shaped structure.

**Outcrop.**—The edges of strata which appear at the surface of the ground are termed their Outcrop or Basset. If the strata are quite horizontal, the direction of outcrop depends on inequalities of the ground and variations in amount of denudation. Perfectly level ground lying upon horizontal beds shows, of course, no outcrop, for the surface coincides with a plane of stratification. But occasional water-courses have been eroded below the general level, so as to reveal along their sides outcrops of the strata. The remarkable sinuosities of outcrop produced by the unequal erosion of horizontal strata are illustrated in Fig. 244, where A is a map of a piece of ground deeply trenched by valleys, and B that of an area comparatively little denuded. In both cases the outcrops are seen to wind round the sides of the slopes.

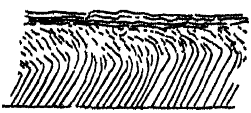


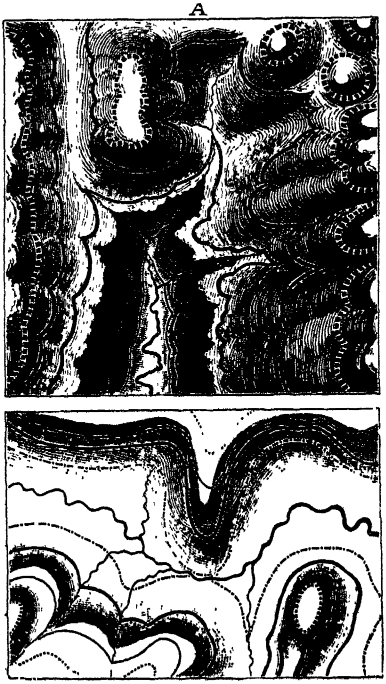
Fig. 243.—Deceptive superficial dip.

Where strata are inclined, the course of their outcrop is regulated partly by the direction and amount of inclination, and partly by the form of the ground. When with low angles of dip they *crop out*, that

is, rise to the surface, along a perfectly level piece of ground, the outcrop runs at a right angle to the dip. But any inequalities of the surface, such as valleys, ravines, hills, and ridges, will, as in the case of horizontal beds, cause the outcrop to describe a circuitous course, even though the dip should remain perfectly steady all the while. If a line of precipitous gorge should run directly with the dip, the outcrop will there be coincident with the dip. The occurrence of a gently shelving valley in that position will cause the outcrop to descend on one side and to mount in a corresponding way on the other, so as to form a V-shaped indentation in its course. A ridge, on the other hand, will produce a deflection in the opposite direction. Hence a series of parallel ridges and valleys, running in the same direction as the dip of the strata underneath, causes the outcrop to describe a widely serpentinous course.

The breadth of the outcrop depends on the thickness of the stratum and on the angle of dip. A bed one foot thick inclined at an angle of 1°, on a perfectly level piece of ground would have an outcrop about 60 feet broad. At a dip of 5° the breadth of the outcrop would be a little over 11 feet. At 30° it would be reduced to 2 feet, and the diminution would continue until, when the bed was on end, the breadth of the outcrop would, of course, exactly correspond with the thickness of the bed.

A



B

Fig. 244.—Sinuous outcrops of horizontal Strata depending on inequalities of surface.
The wavy black lines mark the outcrops of successive conformable horizontal beds.

It is further to be observed that among vertical rocks, the direction of the outcrop necessarily corresponds with the strike, and continues to do so irrespective altogether of any irregularities of the ground. The lower therefore the angle of inclination, the greater is the effect of surface-inequalities upon the line of outcrop; the higher the angle, the less is that influence, till when the beds stand on end it ceases.

**Strike.**—A horizontal line drawn at a right angle to the dip is called the Strike of the rocks. From what has just been said, this line must coincide with outcrop when the surface of the ground is quite level, as on the beach in Fig. 245, and also when the beds are vertical. At all other times, strike and outcrop are not strictly coincident, but the latter wanders to and fro across the former according to changes in the contour

of the ground. The strike may be a straight line, or may curve rapidly in every direction, according to the behaviour of the dip. A set of beds dipping westwards for half a mile (*a* to *b*, Fig. 245) have a north and south strike for the same distance. If the dip changes to S.W., S., S.E., and E., the strike will bend round in a curving line (as at S). In the case of a *quâ-quâ-versal* dip the strike forms a complete circle (as at A). The dip being ascertained gives the strike, but the strike does not certainly indicate the direction of dip, which may be either to the one side or the other.

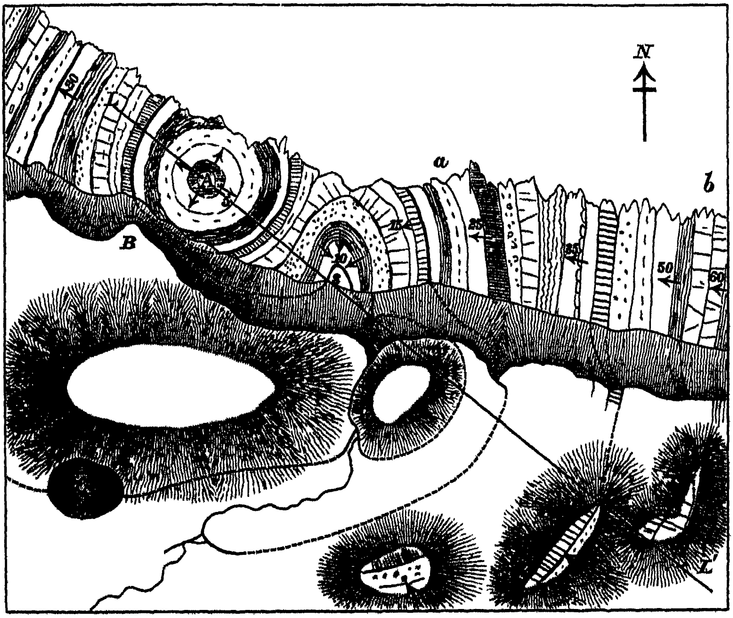



Fig. 245.—Geological Map, showing strata exposed continuously along a beach and occasionally in the interior.

Two groups of strata, dipping the one east and the other west, have both a north and south strike. Strike may be conceived as always a level line on the plane of the horizon, so that, no matter how much the ground may undulate, or the outcrop may vary, or the dip may change, the strike will remain horizontal. Hence in mining operations, it is commonly spoken of as the *level-course* or *level-bearing*. A "level" or underground roadway, driven through a coal-seam at right angles to the dip, will undulate in its trend if the dip changes in direction, but it may be made perfectly level, and kept so throughout a whole coal-field so long as it is not interfered with by dislocations.

In Fig. 245, the strike and outcrop are coincident on the flat beach, but cease to be so the moment the ground begins to slope up into the coast-cliff. This is seen in the eastern half of the map, where the lines of outcrop slant up into the cliff at an angle dependent mainly on the amount of the dip. A section drawn in the line L L' would

show the geological structure represented in Fig. 246. By noting the angles of dip it is possible to estimate the thickness of a series of beds, and how far beneath the surface any given bed might be expected to be found. If, for instance, the horizontal distance across the strike between beds S and A (Fig. 245) were found to be 200 feet, with a mean dip of 15°, the actual thickness would be 51·8 feet, and bed A would be found at a depth of 53·8 feet below the outcrop of S. If the same development of strata continues inland, the bed A should be found at a little more than 200 feet beneath the surface, if a bore were sunk to it in the quarry (Q). If the total depth of rock between *a* and *b* be 1000 feet, then evidently, if the strata could be restored to their original approximately horizontal position, with bed *a* at the surface, bed *b* would be covered to a depth of 1000 feet. It will be noticed also that as the angle of dip increases, the outcrops are thereby brought closer together. Where the outcrops run along the face of a cliff or steep bank (B) they must likewise be drawn together on a map. In reality, of course, these variations take place though the same vertical thickness of rock may everywhere intervene between the several outcrops.

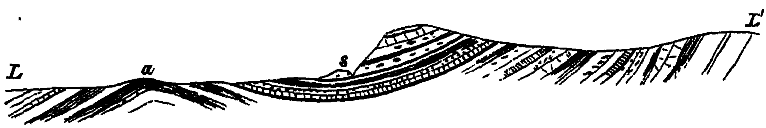



Fig. 246.—Section along the line L L' in Fig. 245.

It is usually desirable to estimate the thicknesses of strata, especially where, as in Fig. 246, they are exposed in continuous section. A convenient though not strictly accurate rule for this purpose may be applied in cases where the angle of inclination is less than 45°. The real thickness of a mass of inclined strata may be taken to be $\frac{1}{12}$ of its apparent thickness for every 5° of dip. Thus if a set of beds dips steadily in one direction at 5° for a horizontal space of 1200 feet measured perpendicularly to the strike, their actual thickness will be $\frac{1}{12}$, or 100 feet. If the dip be 15°, the true thickness will be $\frac{3}{12}$, or 300 feet, and so on.[1]

## Part IV. Curvature.[2]

A little reflection will show that though, so far as regards the trifling portions of the rocks visible at the surface, we might regard the inclined surfaces of strata as parts of straight lines, they must nevertheless be parts of large curves. Take for example the section in Fig. 247. At the left hand the strata descend beneath the surface at an angle of no more than 15°, but at the opposite end the angle has risen to 60°. There being no dislocation or abrupt change of inclination, it is evident that the beds cannot proceed indefinitely downward at the same angle which they have

[1] Maclaren's 'Geology of Fife and the Lothians,' 2nd edit. p. xix. For tables for estimating dip and thickness, see Jukes's 'Manual,' p. 748; Green's 'Physical Geology,' p. 460.

[2] A useful compendium of information regarding geological terms for the dislocations and curvatures of rocks has been prepared by M. E. de Marjerie and Professor A. Heim, 'Les Dislocations de l'Écorce terrestre,' 1888, Zürich (in French and German). A discussion of the various types of plication and dislocation of rocks is given by Bailey Willis in his memoir on "The Mechanics of Appalachian Structure," in the *13th Ann. Rep. U. S. G. S.* 1894; and a later disquisition will be found by C. R. Van Hise in *Journ. Geol.* (1896), iv. pp. 195, 312, 449 and 593.

at the surface, otherwise they would run away from each other, but must bend round to accommodate themselves to the difference of inclination. By prolonging the lines of bedding for some way beneath and above sea-level, we can show graphically that the strata are necessarily curved (Fig. 248). A section of this kind brings out clearly the additional fact that an upward continuation of the curved beds must have been carried away by the denudation of the surface. In every instance therefore where, in

Fig. 247.—Section of Inclined Strata.

walking over the surface, we traverse a series of strata which gradually, and without dislocations, increase or diminish in inclination, we cross part of a curvature in the strata of the earth's crust. The foldings, however, can often be distinctly seen on cliffs, coast-lines, or other exposures of rock (Fig. 249). The observer cannot long continue his researches in the field without discovering that the strata composing the earth's outer crust have been almost everywhere thrown into curves, usually so broad and gentle as to escape observation except when specially looked for.

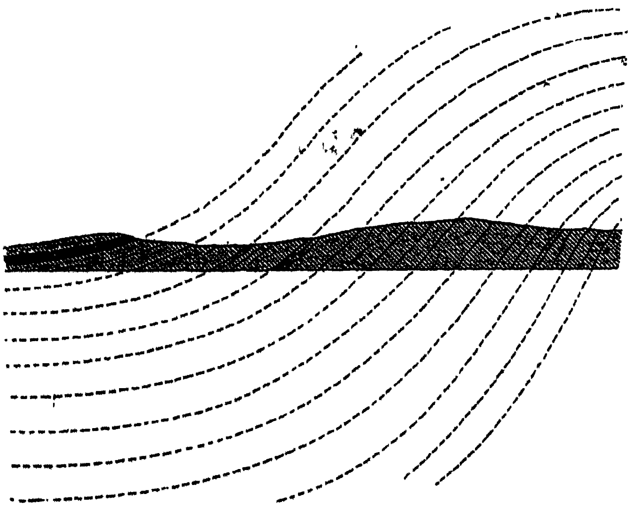


Fig. 248.—Section of Inclined Strata, as in Fig. 247, showing that they form part of a large curve.

If the inclination and curvature of rocks are so closely connected, a corresponding relation must hold between their strike and curvature. In fact, the prevalent strike of a region is determined by the direction of the axes of the great folds into which the rocks have been thrown. If the curves are gentle and inconstant, there will be a corresponding variation in the strike. But should the rocks be strongly plicated, there will

necessarily be the most thorough coincidence between the strike and the direction of the plication.

**Monoclines.**—Curvature occasionally shows itself among horizontal or gently inclined strata in the form of an abrupt inclination, and then an immediate resumption of the previous flat or gently sloping position. The strata are thus bent up and continue on the other side of the fold

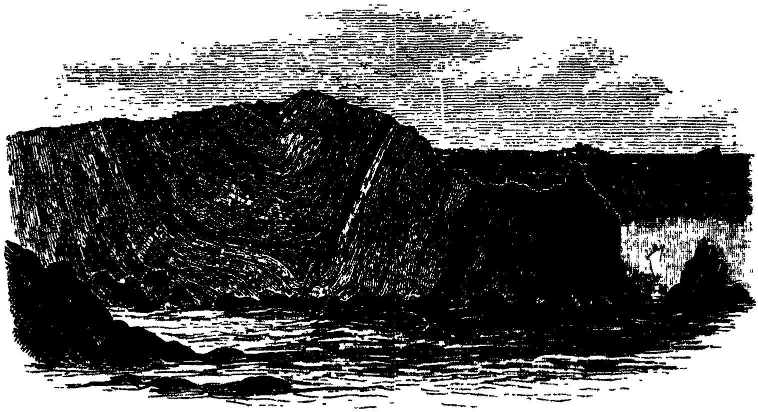


Fig. 249.—Curved Silurian Rocks on the coast of Berwickshire.

at a higher level. Such bends are called Monoclines or monoclinal folds, because they present only one fold, or one half of a fold, instead of the two in an arch or trough (Fig. 279, section 1). The most notable instance of this structure in Britain is that of the Isle of Wight (Fig. 250), where the Cretaceous rocks (*c*) on the south side of the island rapidly rise in inclination till they become nearly vertical, while the Lower Tertiary strata (*t*) follow with a similar steep dip, but rapidly


Fig. 250.—Section of a Monoclinal Fold, Isle of Wight.

flatten down towards the north coast. Probably the most gigantic monoclinal folds in the world are those into which the remarkably horizontal and undisturbed rocks of the Western States and Territories of the American Union have been thrown.[1]

From the abundance of inclined strata all over the world, we may readily perceive that the normal structure of the visible part of the earth's

[1] See the discussions of Messrs. Bailey Willis and Van Hise, cited on p. 672; also Powell's "Exploration of the Colorado River of the West," and "Geology of the Uinta Mountains," in the *Reports* of the United States Geographical and Geological Survey. Dutton's 'High Plateaux of Utah,' and 'History of the Grand Cañon'; Gilbert's 'Geology of the Henry Mountains.'

crust is one of innumerable foldings of the rocks. Sometimes more steeply, sometimes more gently undulated, not infrequently dislocated and displaced, the sedimentary accumulations of former ages everywhere reveal evidence of great internal movement. Here and there, the movement has resulted in the formation of a dome-shaped elevation of the strata, wherein, as if pushed up from a single point, they slope away on all sides from the centre of greatest upthrust, with a *quâ-quâ-versal* dip (pp. 669, 671). Where the top of the dome has been removed, the successive outcrops of the strata form concentric rings, the lowest at the centre, the highest at the circumference, the dip being outwards from the centre (A in Figs. 245 and 246). The converse structure, where the strata have sunk towards a central point, gives rise to a basin in which, after exposure by denudation, the outcrops of the strata likewise form concentric rings, but where the dip is inward to the middle of the basin (*s* in Fig. 246).

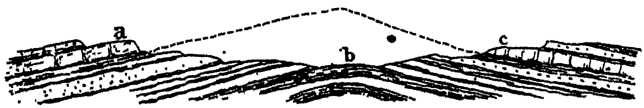



Fig. 251.—Arch, or Anticline, which has been denuded by the removal of beds, as shown by the dotted line *a c* above the axis *b*.

**Anticlines and Synclines.**—In the vast majority of cases, however, the folding has taken place, not round a point, but along an axis. Where strata dip away from an axis so as to form an arch or saddle, the structure is termed an Anticline, or anticlinal axis (Fig. 251). Where they dip towards an axis, forming a trough or basin, it is called a Syncline, or synclinal axis (Fig. 252). In a simple or symmetrical fold the axial plane is vertical or approximately so, and the limbs have

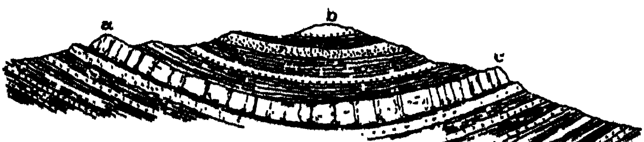



Fig. 252.—Trough, or Syncline, with strata (*a c*) rising from each side of a central axis (*b*).

on the whole the same general angle of inclination in opposite directions (Figs. 251, 252). In many cases, however, the axis is markedly inclined and the dip on one side is much steeper than on the other, though on both sides still towards opposite directions. This inclination may increase until the fold is bent over, so that the strata on one side are inverted and the dip is in the same direction, though it may be at different angles, in the two limbs.

An anticlinal or synclinal axis must always die out unless abruptly terminated by dislocation. In the anticline, the crest of the fold, after continuing horizontal, or but slightly inclined, at last begins to turn downward, the angle of inclination lessens, and the arch then ends or

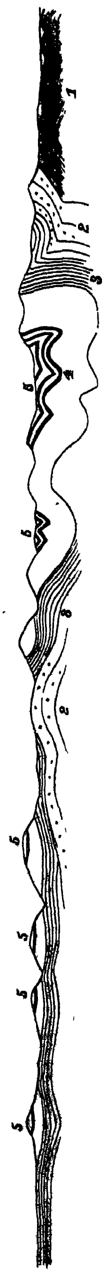


Fig. 253.—Section across the Folded Rocks of the Appalachian Chain (H. D. Rogers).

"noses out." In a syncline, the trough eventually bends upward, and the beds, with gradually lessening angles, swing round it.

**Inversion.**—Inverted folds occur abundantly in regions of great plication. The gradual increase of deformation in a region was admirably illustrated from the Appalachian coal-field by H. D. and W. B. Rogers, who gave an in-

Fig. 254.—Inverted Folds and Isoclinal Structure.

structive demonstration of a series of plications, beginning with symmetrical folds, succeeded by others with steep fronts towards the west, until at last these steeper fronts pass under the opposite sides of the arches, giving rise to a series of inverted folds (Fig. 253). The Silurian uplands of the south of Scotland have the arches and troughs tilted in one direction for miles together, so that in one-half of each of them the strata lie bottom upwards (Fig. 254).[1] It is in large mountain-chains, however, that inversion can be

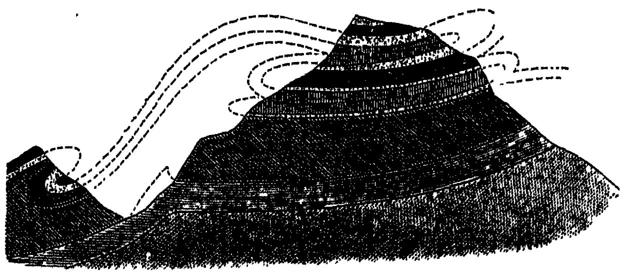


Fig. 255.—Structure of the Glärnisch Mountain, after Baltzer.

seen on the grandest scale. The Alps furnish numerous striking illustrations. On the north side of that chain, the Secondary and Tertiary rocks have been so completely turned over for many miles that the lowest beds now form the tops of the hills, while the highest lie deep below them. Individual mountains (Figs. 255, 256, 257, 258) present

[1] Professor Lapworth has worked out with much skill the inverted anticlines and synclines of the "Moffat Shales" (*Q. J. G. S.* xxxiv. (1878), p. 240), and has pointed out the existence of a similar structure in the Scottish Highlands (*Geol. Mag.* 1883). The structure of the Southern Uplands of Scotland has since been exhaustively described in the Geological Survey Memoir on that region by Messrs. Peach and Horne (1899), where many instructive diagrams will be found.

stupendous examples of inversion, which can be followed with the ey

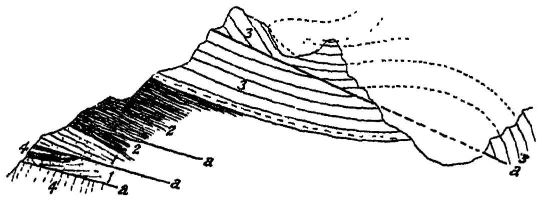



Fig. 256.—Structure of the Glarnisch Mountain, after Rothpletz.
1, Trias; 2, Jurassic; 3, Cretaceous; 4, Eocene and Oligocene. *a*, *a*, Thrust-planes (p. 691).

from a distance along their slopes, as on the declivities on either side of the upper end of the Lake of Lucerne, where great groups of strata

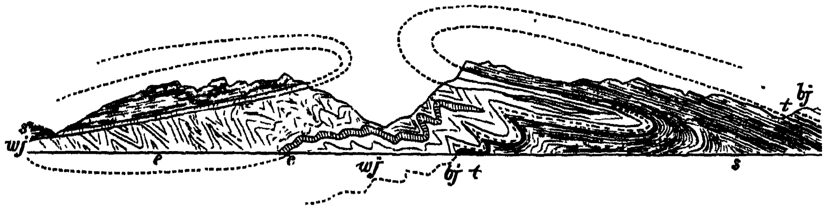



Fig. 257.—Inversion among the mountains south of the Lake of Wallenstadt, Cantons Glarus and St. Gall, according to Professor Heim (compare Fig. 281).
*e*, Eocene; *c*, Cretaceous; *w.j.* White Jura thrust upward on the left hand over the plicated Eocene; *b.j.* Brown Jura; *t*, Trias; *s*, Schistose rocks, perhaps metamorphosed Palæozoic formations.

have been folded over and over each other, as we might fold carpets.[1]

[1] The "Glarner double" fold has been the subject of considerable discussion. The structure, according to Heim, is shown in Fig. 257 ('Mechanismus der Gebirgsbildung'). In his view, the whole of the rocks, schists included, remained undisturbed until the post-Eocene folding. Vacek, however, contended, with evident probability, that the older schists are unconformably overlain by later formations (*Jahrb. Geol. Reichsanst.* 1879, p. 726; 1884, pp. 233, 620; *Verhandl. Geol. Reichs.* 1880, p. 189; 1881, p. 43). A. Heim, *Verhandl. Geol. Reichs.* 1880, p. 155; 1881, p. 204. See also *Arch. Sci. Phys. Nat.*, Geneva, November 1882, p. 24; Lory, *Bull. Soc. Géol. France*, 3me sér. xi, 1882, p. 14. A new and instructive light has been thrown on the structure of this region and of the Alps generally by A. Rothpletz, who has traced numerous "thrust-planes" through the mountains, and has, in my opinion, proved that the so-called double-fold of the Glarus district does not exist, but that the structure is intelligibly explained by a great overthrust fault which he has mapped. His view of the tectonic arrangement of the ground is shown in Fig. 282. (*Z. D. G. G.* 1883, p. 134; 1895, p. 1; 1896, p. 854; 'Ein Geologischer Querschnitt durch die Ost-Alpen, nebst Anhang über die sog. Glarner Doppelfalte,' Stuttgart, 1894; 'Geotektonische Probleme,' Stuttgart, 1894; 'Das Geotektonische Problem der Glarner Alpen,' Jena, 1898, with atlas; 'Geologische Alpenforschungen,' No. 1, Munich, 1900.) In the second edition of the present Text-book (1885) it was pointed out that in Fig. 257 no mere plication could bring the White Jura where it lies comparatively undisturbed on the edge of the excessively plicated Eocene beds, but that it has evidently been pushed over the latter, the line of junction between them being a "thrust-plane." That this is the true structure of the ground has since been shown by Rothpletz. See in particular Plate v. Fig. 4 of his 'Glarner Alpen,' which goes through the same piece of country; and *postea*, p. 693.

Where a series of strata has been so folded and inverted that its reduplicated members appear to dip regularly in one direction, and at the same or nearly the same angles, the structure is termed isoclinal. This structure, illustrated on a small scale among the curved Silurian rocks shown in Fig. 254, occurs on a grand scale among the Alps, where the folds have sometimes been so squeezed together that, when the tops of the arches have been worn away, the strata could scarcely be supposed to have been really inverted, save for the evidence as to their true order of succession supplied by their included fossils. The extent of this compression in the Alps has been already (p. 422) referred to. So intense has been the plication, and so great the subsequent denudation, that portions of Carboniferous strata appear as if regularly interbedded among Jurassic rocks, and indeed could not be separated save after a study of their enclosed organic remains.

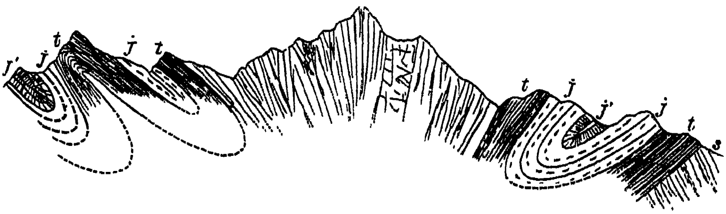



Fig. 258.—Fan-shaped structure, Central Alps.
*j'*, Upper Jurassic Limestone; *j*, Brown Jura and Lias; *t*, Trias; *s*, Schistose rocks.

A further modification of the folded structure is presented by the fan-shaped arrangement (*structure en éventail*, *Fächer-Falten*) into which highly plicated rocks have been thrown. The most familiar example is that of Mont Blanc, where the sedimentary strata at high angles seem to dip under the crystalline schists (Fig. 258).[1]

The larger simple flexures of the terrestrial crust, involving a wide region in each fold where the movement has been one of subsidence or uplift without any marked deformation, such as rapid plication and inversion, may be termed *Geanticlines* and *Geosynclines*, to use the names proposed by Dana. Where the flexures are not simple, but on the contrary involve many plications, and have thus been accompanied with considerable disturbance and often with intense deformation, they were termed by the same geologist *Anticlinoria* and *Synclinoria*. Thus the

[1] Besides the works on mountain-structure cited in the foregoing pages, see F. M. Stapff, "Zur Mechanik der Schichtenfaltungen," *Neues Jahrb.* 1879, pp. 292, 792; the fine series of sections illustrating various features of the Alps in the plates accompanying the 'Matériaux pour la Carte géologique de la Suisse,' especially Livraison xvi. on the *Vaudois Alps*, by Professor Renevier; Livraison xxi. by E. Favre and Schardt, on *Canton de Vaud*, &c., and xxv. (1891), by A. Heim on the *High Alps between Reuss and Rhine*. Other essays have been published by M. Bertrand in *Bull. Carte Géol. France*, No. 24 (1891); *B. S. G. F.* xxii. (1894), pp. 69-162; MM. Bertrand and Golliez, *op. cit.* xxv. (1897), p. 568; E. Ritter, *Bull. Carte Géol. France*, No. 60 (1897-98); L. Duparc and L. Mrazec, "Recherches géol. pétrog. Massif du Mont Blanc," *Mém. Soc. Phys. Hist. Nat. Genève*, xxxiii. No. 1, 1898. The subject of dislocation in mountain-structure is referred to, *postea*, p. 692.

wide region in which by long-continued subsidence and deposition the geological formations of Central Europe were laid down may be termed

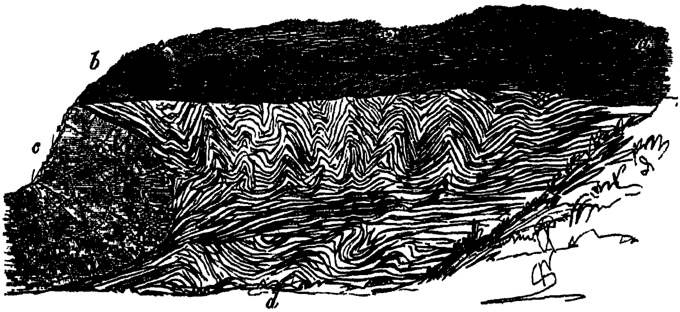



Fig. 259.—Locally crumpled Strata near a Fault, Dalquharran, Ayrshire. *d*, shales; *c*, limestone; *b*, boulder-clay.

a geosyncline. Subsequent terrestrial disturbance upraised the complicated chain of the Alps, which forms a gigantic Anticlinorium, while

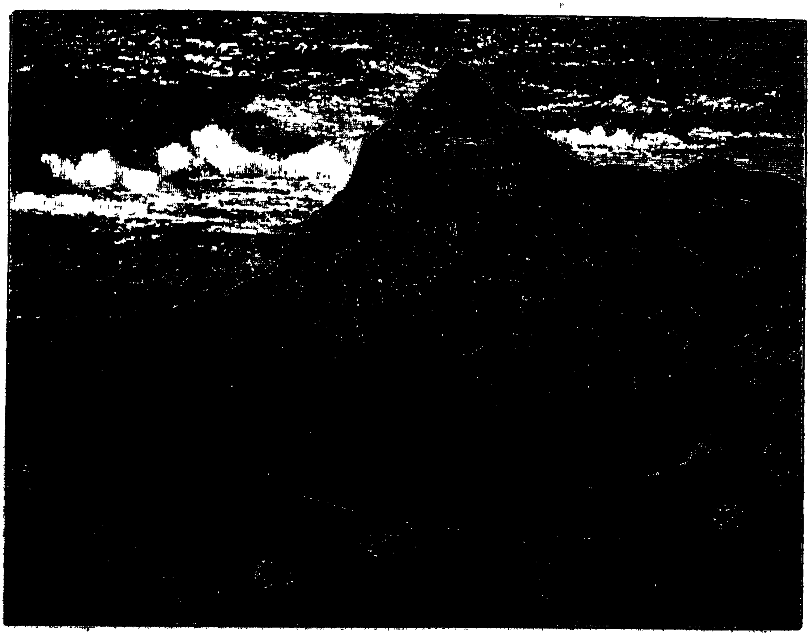


Fig. 260.—Contorted Rocks, east end of Lake Minnewonka, Banff, Canadian Pacific Railway.

the wide central valley between that chain and the parallel anticlinorium of the Jura mountains is a Synclinorium.[1]

**Crumpling.**—In the general plication of a district there are usually

[1] Dana's 'Manual of Geology'; Van Hise, *Journ. Geol.* iv. p. 319.

localities where the pressure has been locally so intensified that the strata have been corrugated and crumpled, till it becomes almost impossible to follow out any particular bed through the disturbed ground. On a small scale, instances of such extreme contortion may now and then be found

Fig. 261.—Piece of Alpine Limestone, showing fine puckering produced by great lateral compression (real size).

at faults and landslips, where fissile shales have been corrugated by subsiding heavy masses of more solid rock (Fig. 259). But it is, of course, among the more plicated parts of mountain-chains that the structure receives its best illustrations. Few travellers who have passed the upper end of the Lake of Lucerne can have failed to notice the remarkable cliffs of contorted rocks near Fluelen. But innumerable examples of equal or even superior grandeur may be observed among the more preci-

Fig. 262.—Crumpled Triassic Rock, Tödi group, Switzerland (real size).

pitous valleys of the Swiss Alps. Striking illustrations of the same structure may be found in many other great mountain-chains (Fig. 260). No more impressive testimony could be given to the potency of the force by which mountains were upheaved. And yet, striking as are these colossal examples, involving as they do whole mountain-masses in their folds, their effect upon the mind is even heightened when we discover that such has been the strain to which solid limestones and other rocks have been subjected that even their finer layers have been intensely puckered. Some

of these minor crumplings are readily visible to the eye in hand-specimens (Figs. 35, 261, 262). But in many foliated, crumpled rocks the puckering is so minute as to be best seen with the microscope (Fig. 36). Frequently the puckerings have been ruptured and a fine cleavage or jointing has been produced (Ausweichungsclivage, strain-slip cleavage).

It may often be observed that in strata which have been intensely crumpled, the same bed is reduced to the smallest thickness in the arms of the folds, but swells out at the bends as if squeezed laterally into these loops. This change of form is more especially observable in softer strata intercalated among others of greater powers of resistance. It is remarkably developed in some coal-fields, where the rocks have undergone considerable lateral compression, the coal-seams as the least resisting members of the series being then subjected to extreme variations in thickness, sometimes increasing to far more than their normal dimensions in the loops of the folds (*a a*, in Fig. 263), and almost disappearing in the limbs.[1]


Fig. 263.—Unequal compression of Coal in crumpling, Pembrokeshire (*B.*).

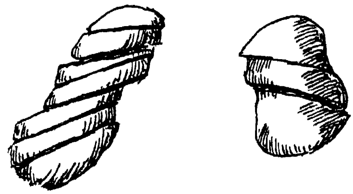


Fig. 264.—Pebbles of quartz in an Old Red Sandstone conglomerate, sliced through by crushing movements, Cushendun, Antrim (¼ nat. size).

**Deformation and Crushing.**—During the intense shearing movements which take place at great depths within the terrestrial crust, rocks lie above their elastic limit, but under too great a pressure to be crushed into pieces. They consequently acquire a certain amount of plasticity, and their individual particles have been compressed, elongated, and made to move past each other, as is instructively shown by the deformation of pebbles and of fossils (p. 419). Where the elastic limit of the rocks has been passed under an insufficient overlying load, rupture has taken place, as in the familiar examples furnished by the pebbles of conglomerates, which even when composed of the most solid quartzite may be seen to have been sliced through by a succession of fractures. Striking examples of this structure are furnished by the crushed Old Red Sandstone of the north-east of Ireland (Fig. 264).

Where the distortion has taken place slowly under a sufficient weight of overlying material, a process of shearing has been induced whereby the original structure of the rocks may be entirely replaced by the shear-

[1] Good examples are supplied by the much-disturbed Franco-Belgian coal-field; see, for instance, a paper by M. Lohest, "Sur le Mouvement d'une Couche de Houille entre son Toit et son Mur," *Ann. Soc. Géol. Belg.* xvii. (1890), p. 125. For illustrations of this structure, as shown in mountain-chains, see Heim's 'Mechanismus der Gebirgsbildung,' where a terminology for the different parts of folds is given.

structure already noticed (p. 418). Massive coarsely crystalline pegmatites may be traced through successive stages wherein the component orthoclase and felspar are more and more crushed and drawn out, until in the end the rock becomes a compact finely fissile schist, with a peculiar thready or streaky structure, which can hardly be distinguished from the flow-structure of a rhyolite (Fig. 265). This change is more particularly developed along great thrust-planes, but may be observed throughout a mass of rock that has undergone intense shearing.

In many cases, where the rocks may be supposed to have lain between the zones of crushing and plasticity, lenticular "eyes" of the original rock have been left little or not at all affected, while the portions between them have been crushed and rolled out, and have re-crystallised more or

Fig. 265.—Shear-structure. Torridon Sandstone, Loch Keeshorn. Mag. 30 diam. (drawn by Mr. F. W. Rudler). The felspars and other grains have been crushed and flattened, and the matrix made to move past them as in flow-structure. (Compare Fig. 80.)

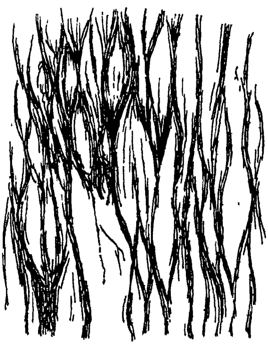


Fig. 266.—Diabase crushed into lenticles which retain most of their original structure, while the more sheared material between them has passed into a chloritic schist: Guldalen, Norway. The portion of rock here represented is 10 feet high by 8 feet broad.

less completely as true schists (Figs. 266, 367). The large felspars of augengneiss afford, on a small scale, examples of this structure. From these every gradation of size may be traced up to huge blocks of the original rock, which have preserved their structure though completely enclosed in comminuted and often schistose material. Sections showing the close connection between mechanical crushing and the production of a schistose structure may be seen abundantly among the Scottish Highlands.[1] In the Silurian district of Guldalen, Norway, diabases and other igneous rocks also exhibit every stage in the crushing down of eruptive material and its conversion into schists (Fig. 266). Similar structures are well displayed among the schists and their accompaniments in Anglesey.

Not only are the individual particles of rocks drawn out by shearing, but in the complicated process of mountain-building, larger features of geological structure likewise undergo deformation. The anticlinal and

[1] *Q. J. G. S.* xliv. (1888), p. 392; and *postea*, Book VI. Part I. § ii.

synclinal folds developed in the earlier stages of the process are sometimes bent over and crushed together, so as to be nearly or completely effaced. Rocks which normally lie one upon the other with the most violent unconformability may be found crushed together, with their original structures more or less completely effaced and a new parallel structure developed in them, insomuch that they might easily be mistaken for contemporaneous and perfectly conformable formations. Thus in the north-west of Scotland the nearly horizontal Torridon Sandstone lies on the upturned edges of the much more ancient Lewisian Gneiss, as shown in Figs. 344 and 369. But where the strongly unconformable junction has come into one of the great crush-lines it has been effaced and a new parallel shear-structure has been developed in both rocks (Fig. 267).

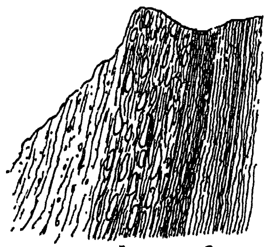



Fig. 267.—Unconformable junction of Torridon Sandstone and Lewisian Gneiss crushed into apparent conformability. Head of Strath Oykil, Sutherland.
*a*, gneiss with its original structure destroyed and a new foliation produced parallel with that superinduced in the conglomerate (*b*).

Where rocks lie under too light a load to become plastic, and have, therefore, given way to great crushing by breaking to pieces, their broken fragments may be pushed along shear-planes or belts of movement, and may thus be pressed against each other and rolled forward, until their edges are rounded off and they acquire much resemblance in general form to the pebbles of a conglomerate. Bands of such comminuted materials are of not infrequent occurrence among Palæozoic and older formations which have suffered much disturbance. They are known as *Crush-conglomerates* or, where the fragments are angular, as *Crush-breccias* (friction-breccias). They have been mistaken for aqueous conglomerates, and this mistake was hardly avoidable until the extent to which the earth's crust has been deformed had been realised. They may be distinguished from true conglomerates by the local derivation of their materials, which have come from the immediately adjacent rocks, by the general absence of the smooth-rolled water-worn surfaces that characterise the stones of aqueous conglomerates, and in many cases by an obvious transition from the broken-up fragments to the more solid remaining rock from which they were derived.[1]

As already stated, various experiments have been devised to illustrate the facts of mountain-structure. By a combination of parallel layers of different substances exposed to lateral compression and tension it is

[1] G. W. Lamplugh, *Q. J. G. S.* li. (1895), p. 563; lvi. (1900), p. 11; A. G., *Geol. Mag.* 1896. p. 481; J. B. Hill, *Q. J. G. S.* lvii. (1901), p. 313; C. R. Van Hise, *Journ. Geol.* iv. (1896), p. 624. The term "autoclastic" has been proposed for these rocks. H. L. Smyth, *Amer. Journ. Sci.* 3rd ser. xlii. p. 331. Some good illustrations of the pseudo-conglomerates in the Archæan rocks of Ontario are given in a paper by A. E. Barlow, *Ottawa Naturalist* xii. (1899), p. 205. The subject of autoclastic rocks and their discrimination from ordinary breccias and conglomerates is discussed by C. R. Van Hise in *16th Amer. Rep. U. S. G. S.* (1896), p. 679.

possible to imitate many of the features of that structure and to produce very instructive diagrams.[1]

**Tension-ruptures.**—In the course of the movements that take place within the terrestrial crust it must here and there happen that instead of being driven together so as to occupy smaller space, rocks are pulled out and made to take up rather more room. Tension of this kind must occur on the crests of anticlines and the tops of the loops of rapid plications, and may often lead to rupture of the bent rocks along the line of greatest strain. The cracks thus produced are eventually filled with quartz, calcite or other mineral substances, usually introduced by infiltrating water. Hence in a region of much-folded rocks parallel lines of mineral veins may often be observed along the bands of greatest tension. Occasionally rocks have been split up by rows of parallel rents, as if they had been pulled asunder. Remarkable examples of this structure are presented by the Torridon Sandstone in the west of Ross-shire, where the rents have been filled in some cases with quartz, in others with a pegmatitic admixture of quartz and pink felspar, probably derived from the surrounding rock, which is an arkose.

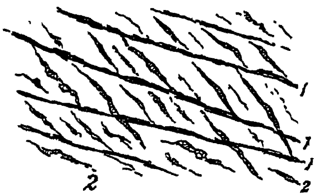



Fig. 268.—Parallel Quartz-veins along a belt of tension. Torridon Sandstone, Loch Carron, Ross-shire.
1, 1, planes of bedding; 2, 2, rents filled with quartz. These usually are confined each to one bed of sandstone, but occasionally traverse more than one.

## PART V. CLEAVAGE.

Cleavage-structure having been described at p. 417, we have to notice here the manner in which it presents itself on the large scale among rock-masses. The direction of cleavage usually remains persistent over considerable regions, and, as was shown by Sedgwick,[2] corresponds, on the whole, with the strike of the rocks. It is, however, independent of bedding. Among curved rocks, the cleavage-planes may be seen traversing the plications without sensible deflection from their normal direction, parallelism, and high angle. They must thus be strictly later than these plications. But their general coincidence with the trend of the axes of

[1] See *ante*, p. 422, where the experiments of Hall, Favre and Cadell are noticed. The ample series of plates accompanying Mr. Bailey Willis' memoir on the mechanics of Appalachian structure cited on p. 672 give a vivid picture of the experimental results obtained by him. Consult also Mr. Mellard Reade's 'Origin of Mountain Ranges,' 1886.

[2] "On the Structure of large Mineral Masses," *Trans. Geol. Soc.* 2nd ser. iii. (1835)—an admirable memoir, in which the structure of a great cleavage region is clearly and graphically described. Phillips gave a good summary of our knowledge up to 1856 in his "Report on Cleavage" in the *British Assoc. Rep.* for that year. An exhaustive memoir on the subject by Mr. A. Harker (*Rep. Brit. Assoc.* 1885, p. 813) contains copious references to the bibliography. See also Rev. O. Fisher, *Geol. Mag.* 1884-85, and 'Physics of the Earth's Crust.' G. F. Becker, *Journ. Geol.* iv. (1896), p. 429; C. R. Van Hise, *op. cit.* p. 449. An excellent account of a large area of cleaved rocks will be found in T. N. Dale's "Slate Belt of Eastern New York" in *19th Ann. Rep. U. S. G. S.* (1899).

folding serves to indicate a community of origin for cleavage and folding, as concomitant though not perhaps always simultaneous effects of the lateral compression of rocks.[1] Among curved strata, the planes of cleavage sometimes coincide with, and are sometimes at right angles to, the planes

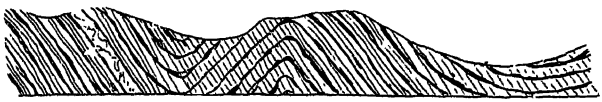



Fig. 269.—Curved and contorted Devonian Rocks, near Ilfracombe (*B.*).
Bedding and cleavage planes are coincident at *a* and *c*, but nearly at right angles at *b*.

of bedding, according to the angles of the folding (Fig. 269). The persistence of cleavage-planes across even the most diverse kinds of rock, both sedimentary and igneous, was first described by Sedgwick. Jukes also pointed out that over the whole of the south of Ireland the trend of the cleavage seldom departs 10° from the normal direction E. 25° N., no matter what may be the differences in character and age of the rocks which it crosses. But though cleavage is so persistent, it is not equally well developed in every kind of rock. As already explained (p. 418), it is most perfect in fine grained argillaceous rocks, which have been altered by it into slates. It is often well developed in felsites and other igneous rocks, which then furnish good flags or even slates. It may be observed at once to change its character as it passes from fine-grained rocks into others of more granular texture (Figs. 83, 84). Occasional traces of distortion or deviation of the cleavage-planes may be observed at the contact of two dissimilar kinds of rock (Fig. 271). In the case of coarse-grained rocks, the large particles may be observed to have been shifted so as to lie with their long axes parallel with the planes of cleavage, even when these planes may be at right angles to those of stratification. In conglomerates, for example, it is common to find that the pebbles have been turned round so as all to lie in new planes coincident with those of the cleavage of the adjacent finer-grained strata. Remarkable examples of this alteration may be seen near Westport, County Mayo, where some conglomerates and grits have been violently plicated and cleaved (Fig. 270).

Fig. 270.—Plicated and cleaved Conglomerates and Grits (? Lower Silurian), showing the independence of bedding and cleavage and the rearrangement of the pebbles in the direction of cleavage, 2½ miles east of Westport, County Mayo.

A region may have been subjected at successive intervals to the

[1] Harker, *Brit. Assoc. Rep.* 1885, p. 852.

compression that has produced cleavage. The Silurian rocks of the south-west of Ireland were upturned, and probably cleaved, before the deposition of the Old Red Sandstone, which has in turn been well

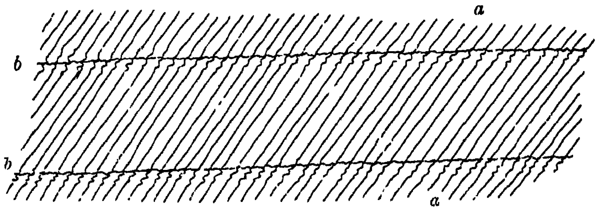



Fig. 271.—Cleaved Strata, Wiveliscombe, West Somerset (*B.*).
Showing the cleavage-lines *a a* slightly undulating at the partings of the strata *b b*.

cleaved.[1] Evidence of the relative date of cleavage may be obtained from unconformable junctions and from conglomerates. An uncleaved series of strata, lying upon the denuded edges of an older cleaved series, proves the date of cleavage to be intermediate between the periods of the two groups. Fragments of cleaved rocks in an uncleaved conglomerate show that the rocks whence they were derived had already suffered cleavage, before the detritus forming the conglomerate was removed from them. An intrusive igneous rock, traversed with cleavage-planes like its surrounding mass, points to cleavage subsequent to its intrusion (Fig. 272).[2]

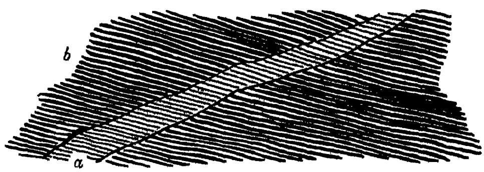



Fig. 272.—Vein of Porphyry (*a*) crossing Devonian Slates (*b*), Plymouth Sound, both being traversed by cleavage (*B.*)

Between cleavage and foliation there is in many cases a close relation. Microscopic examination of some cleaved rocks shows that in original clastic sediment a micaceous mineral has been abundantly developed, the plates of which are ranged along the planes of cleavage. This mica can be distinguished from original mica-flakes in the sediment. It may be observed, in many cases, to impart a lustrous silvery or silky sheen to the cleavage-faces of a slate, yet may be at right angles to the original lamination of deposit. Such a crystalline re-arrangement is indeed an incipient foliation. It is the same structure, further developed and intensified, which gives their distinctive character to schists. The crystalline metamorphosis naturally proceeds along the lines of least resistance, which in cleaved rocks are the cleavage-planes, and in uncleaved sedimentary rocks are the planes of deposition. Foliation, as already remarked (p. 428), may sometimes represent stratification, some-

[1] De la Beche, 'Geol. Observer,' p. 620. [2] *Ibid.* p. 621.

times cleavage, and sometimes divisional planes superinduced by shearing or faulting.[1]

Before passing from this subject it may be well to note how deceptive is the resemblance of cleavage-planes to bedding, especially on weathered exposures of rock, where perhaps the original bedding has been obscured or obliterated. At first sight, for instance, a portion of a group of slates (*a* in Fig. 273) seen by itself might be supposed to consist of highly inclined vertical strata. But further examination of this section would


Fig. 273.—Deceptive appearance of Unconformability where a group of uncleaved grits (*b*) rests on a group of highly cleaved slates (*a*), West Coast of Islay.

disclose lines of sediment or of colour, marking the stratification which here undulates in an anticlinal fold; while an overlying group of grits (*b*) that had resisted cleavage, and seemed to be lying unconformably on the edges of the slates, would be seen to be a perfectly conformable deposit.

Experienced observers have been misled by this resemblance. At Llanberis, for example, the lower portion of a section consists of volcanic tuff and the upper of conglomerate. The tuff being compact and fine-grained, has undergone such decided cleavage that at first the flags into which it is divided by the cleavage-planes might be mistaken (as they have in fact been) for bedding, and the conglomerate would then be regarded as a much younger deposit lying unconformably on the tuff. In reality, however, the tuff coincides in its bedding with the conglomerate; they are parts of one continuous series, but the coarse-grained conglomerate has been only slightly affected by the pressure which induced perfect cleavage in the tuff.[2]

## PART VI. DISLOCATION.

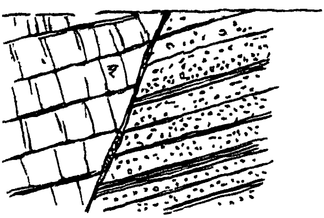
The movements which the crust of the earth has undergone have not only folded and corrugated the rocks, but have fractured them in all directions. The dislocations may be either simple **Fissures**, that is, rents without any vertical displacement of the mass on either side, or **Faults**, that is, rents where one side has been moved relatively to the other.[3] It is not always possible, in a shattered rock, to discriminate

[1] See Sedgwick, *Trans. Geol. Soc.* (2), iii. p. 461. Darwin on foliation and cleavage, 'Geological Observations in South America,' 1846, p. 162. A. C. Ramsay, "Geology of North Wales," *Mem. Geol. Survey*, vol. iii. 2nd edit. p. 283. F. M. Stapff, *Neues Jahrb.* 1882 (i.), p. 82.

[2] See this locality figured in 'Ancient Volcanoes of Great Britain,' vol. i. p. 163.

[3] The student of this department of geology will find in the joint essay by M. E. de Margerie and Professor Heim, cited on p. 672, a valuable handbook of the terms used to describe

etween joints and those lines of division to which the term fissures is ore usually restricted. Many so-called fissures may be merely enlarged joints. It is common to meet with traces of friction along the walls of fissures, even when no proof of actual vertical displacement can be gleaned. The rock is then often more or less shattered on either side, and the contiguous faces present rubbed and polished surfaces (slickensides, p. 661). Mineral deposits may also commonly be observed encrusting the cheeks of a fissure, or filling up, together with broken fragments of rock, the space between the two walls. The structure of mineral veins in fissures is described in Part IX.



ig. 274.—Section of sharply defined Fault without contortion of the rocks.

**Nature of Faults.**—In a large proportion of cases, however, there has een not only fracture but displacement. The rents have become faults s well as fissures. The movement may have affected only one side of the issure, or both sides. Sometimes it has consisted in a mere vertical subsidnce of one side; in other cases, one side has been pushed up, or while

Fig. 275.—Section of a Fault, showing disturbance of rocks.

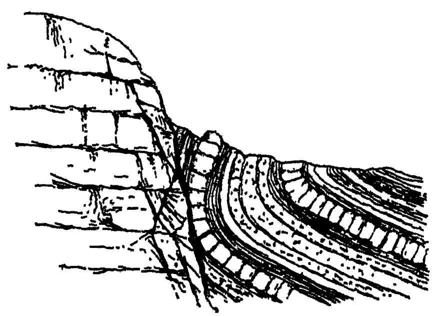


Fig. 276.—Section of Fault with inverted beds on the downthrow side.

one side has moved upward the other has sunk downward, or both sides have been shifted up or down from their original position, but one more than the other. In ordinary faults the displacement is usually vertical or nearly so. But in some regions faults have been produced by a lateral thrust of one side of a fissure past the other side. This structure comes out with remarkable prominence in the gneiss district of Western Sutherland, where dykes crossed by such lateral thrusts are disrupted and drawn out

the various structures arising from ruptures of the terrestrial crust. Some definition of terms n regard to faults are also given by J. E. Spurr in a paper on "The Measurement of Faults," *Journ. Geol.* v. (1897), p. 723.

along the line of fissure so as to be reduced to a $\frac{1}{45}$ part of their ordinary breadth.[1]

Faults on a small scale are sometimes sharply defined lines, as if the rocks had been sliced through and fitted together again after being shifted. In such cases, however, the harder portions of the dislocated rocks will usually be found slickensided. More frequently some disturbance has occurred on one or both sides of the fault (Fig. 275). Sometimes, in a series of strata, the beds on the side which has been pushed up (or side of upthrow) are bent down against the fault, while whose on the opposite side (or that of downthrow) are bent up (Fig. 276). Most

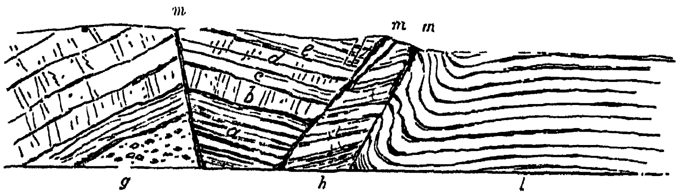



Fig. 277.—Section of group of Faults, coast of Glamorganshire, west of Lavernock Point (*B.*).
*m m m*, three adjacent faults by which the inclination of the strata is shifted and some of the beds are crumpled; *a*, dolomitic limestone and marl; *b*, *c*, *d*, *e*, *f*, dolomitic limestone; *g*, dolomitic conglomerate; *h*, beds corresponding with those on the left; *l*, Lias, thrown in by a "reversed" fault.

commonly the rocks on both sides are considerably broken, jumbled and crumpled, so that the line of fracture is marked by a belt or wall-like mass of fragmentary rock, known as "fault-rock." Where a dislocation has occurred through materials of very unequal hardness, such as solid limestone bands and soft shales, or where its course has been undulating, the relative shifting of the two sides has occasionally brought opposite prominences together so as to leave wider interspaces (Fig. 346). The actual breadth of a fault may vary from a mere chink into which the point of a

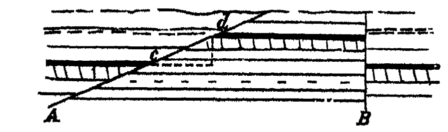



Fig. 278.—Section of inclined and vertical Faults.

knife could hardly be inserted, up to a band of broken and often consolidated materials many yards wide. Where a fault has a considerable throw, it is sometimes flanked by parallel small faults. The occurrence of these close together will obviously produce the appearance of a broad zone of much fractured rock along the trend of a main fissure. A line of disturbance may consist of several parallel faults of nearly equal magnitude (Fig. 279, section 3).

[1] See Report on Geological Survey work, *Quart. Journ. Geol. Soc.* xliv. (1888), p. 393; and *postea*, Fig. 366.

Faults are sometimes vertical, but are generally inclined. The largest faults, or those with the greatest vertical *Throw* or displacement (p. 694), commonly slope at high angles, while those of only a few feet or yards may be inclined as low as 18° or 20°. The inclination of a fault from the vertical is called its *Hade*. In Fig. 278, for example, the fault at B, being vertical, has no hade, but that at A hades at an angle of 70° from the vertical to the left hand. The amount of throw is represented as the same in both instances, but with the direction of throw to opposite quarters, so that the level of the beds is raised between the two faults above the uniform horizon which it retains beyond them.

The effect of the inclination of faults is to give the appearance of lateral displacement. In Fig. 278, for example, where the hade of one fault is considerable, the two severed ends (*c* and *d*) of the black bed appear to have been pulled asunder. The horizontal distance to which they are removed does not depend upon the amount of vertical displacement, but upon the angle of hade. A small fault with a great hade will shift strata laterally much more than a large fault with a small hade. It is obvious that the angle of hade must seriously affect the value of a coal-field. If the black bed in the same figure be supposed to be a coal-seam, it could be worked from either side up to *c* and *d*, but there would be a space of barren ground between these two points, where the seam never could be found. The larger the angle of hade the greater the breadth of such barren ground.

**Different Classes of Faults.**—There are two great classes of faults: (1) those in which gravity plays a chief part and one side subsides (Normal Faults), and (2) those in which, consequent upon compression within the terrestrial crust, portions of this crust are pushed up over other parts (Reversed Faults, Overthrusts).

1. Normal Faults.—In the vast majority of cases, faults hade in the direction of downthrow, or in other words, they slope away from the side which has risen. These are *Normal Faults*. The explanation of the structure is doubtless to be found in the fact that the portion of the terrestrial crust towards which a fault hades presents a less area of base to pressure or support from below than the mass with the broad base on the opposite side, and consequently in obedience to gravity sinks down along the plane of the fault. The mere inspection of a fault in any natural or artificial section suffices, in most cases, to show which is the upthrow side. In mining operations, the knowledge of this rule is invaluable, for it decides whether a coal-seam, dislocated by a fault, is to be sought for by going up or down. In Fig. 278, a miner working from the left, and meeting with the fault at *c*, would know from its hading towards him that he must ascend to find the coal. On the other hand, were he to work from the right, and catch the fault at *d*, he would see that it would be necessary to descend. According to this rule, a normal fault never brings one part of a bed below another part, so as to be capable of being pierced twice by the same vertical shaft.

2. Reversed Faults or Overthrusts are those in which lower rocks on one side have been pushed over higher rocks on the other. In

these cases, the same stratum may be pierced twice by a vertical shaft. The hade is therefore in the direction of upthrow, but is often so low in angle that the plane of the fault (thrust-plane) becomes nearly flat or even undulating. Faults of this kind chiefly occur in regions where the rocks have been excessively plicated, and especially where one-half of a fold has been pushed over another (Figs. 277 and 279, section 4).[1]

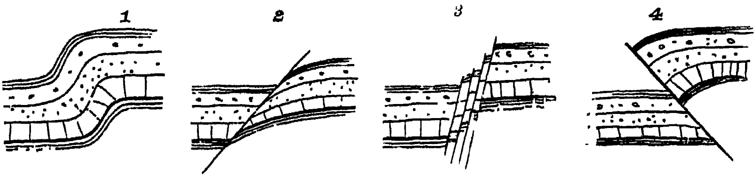



Fig. 279.—Sections to show the relations of Monoclinal Folds and Faults.
1, Monoclinal fold; 2, Monoclinal fold replaced by a single normal fault; 3, Monoclinal fold converted into a series of parallel normal faults; 4, Monoclinal fold developed by increase of plication into a reversed fault.

They are closely connected with anticlinal and synclinal folding. Thus, a monoclinal fold may by increase of lateral pressure be developed into a reversed fault. Beautiful examples of this relation have been observed by Powell and others among the little-disturbed formations of the great plateaux of Utah and Wyoming. On a smaller scale excellent

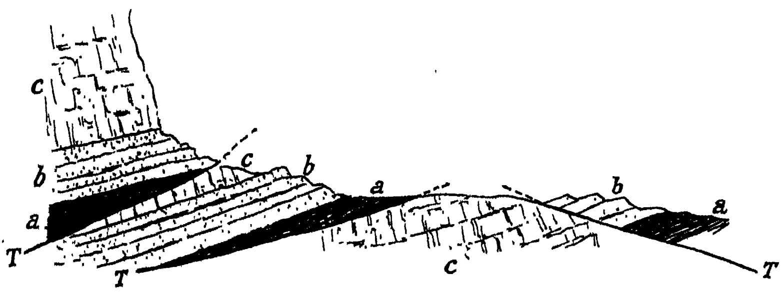



Fig. 280.—Overthrusts in the Upper Cretaceous formations, Shore, Eastbourne.
*a*, gault; *b*, greensand; *c*, chalk. T T, thrust-planes.

illustrations of overthrusts with low thrust-planes may be found among the comparatively little disturbed Cretaceous and Tertiary formations of the south of England. Fig. 280, for example, represents two thrust-planes

[1] If faults were generally due to rupture from compression we should expect the "reversed" to be the ordinary form. The normal hade of faults points to the existence of stresses in the crust of the earth which are from time to time relieved by dislocation. But the nature of these stresses and the manner in which faults arise are still among the obscure problems of geology. The first recognition of a reversed fault or overthrust appears to have been by the mineralogist C. S. Weiss, who in October 1826 found near Dresden an old granite which had been pushed over the Cretaceous strata. See Rothpletz, *Compt. rend. Congrès Géol. Internat. Zurich* (1897), p. 252.

which are exposed on the shore to the west of Eastbourne. It will be seen that in each case the Gault and Greensand have been pushed up so as to overlie the Chalk which normally comes above them both.[1]

It is in mountainous regions, where rocks have undergone the greatest amount of disturbance, that overthrusts are most abundantly developed; they become there, indeed, the more common type of dislocation. In the Alps, for example, they may be observed of all dimensions, from the most trifling movement, amounting to only a few inches or feet, up to the most gigantic displacements. Excellent examples of the minor kind are conspicuous on the limestone walls of the valley of Lauterbrunnen (Fig. 281), where the Jurassic strata have been sliced through by many gently inclined thrust-planes, along which the shifted rocks fit close without any crushed material between them. From such unimportant faults in the general tectonic structure of the ground, stages of increasing magnitude may be traced in a mountain-chain, until we are brought face to face with some of the most gigantic horizontal displacements, whereby large mountainous masses of the terrestrial crust have been thrust over younger formations, in some cases for a distance of many miles.

Remarkable illustrations of this structure have been carefully studied and mapped in the north-west of Scotland. The oldest (Archæan) rocks have there been driven forwards for miles upon gently inclined thrust-planes, and now lie upon the younger (Cambrian and perhaps Silurian) formations (Figs. 344, 362, 366, 369). Such a structure points to enormous tangential pressure, by which the very foundations of the country were torn up and thrust towards the surface. Subsequent denudation having carved the ground into mountains and valleys, the strange spectacle is now presented of outlying cakes of the very oldest rocks that cap the heights, and look as if they lay normally on the much younger formations beneath them. These gently inclined or even undulating overthrusts (thrust-planes) have been displaced by younger normal faults, precisely as if they had been planes of stratification. In many places, so intense have been the mechanical movements that extensive metamorphism has been induced by them. Along the thrust-planes, and for some way above them, the rocks that have been pushed forward have undergone enormous shearing. As above remarked (p. 683), their original structures have been effaced, new divisional planes have been developed in them, and they have become more or less schistose along new foliation-planes, the new minerals crystallising along the shearing-surfaces approximately parallel to the thrust-planes. A general idea of the complication of this structure may be obtained from Fig. 369, where it will be observed that successive slices of the rocks have been ruptured and pushed towards the left hand on numerous minor thrusts at comparatively high angles, and that over these come much more powerful thrusts at lower angles, by which the older rocks are driven across the younger.[2]

This kind of structure has been shown by Rothpletz to play an important part in

[1] A. Strahan (*Q. J. G. S.* li. (1895), p. 549, and "Geology of the Isle of Purbeck" in *Mem. Geol. Surv.*) has described a series of thrust-planes farther west in the Chalk exposed along the coast-line of the Isle of Purbeck. The examples at Eastbourne were first detected and mapped by Mr. Clement Reid.

[2] B. N. Peach and J. Horne, *Nature*, 13th Nov. 1884. The details of this structure with numerous illustrations will be found in the Report of the Geological Survey, *Q. J. G. S.* xliv. (1888), p. 378. A detailed memoir on the North-West Highlands is in preparation by the Survey. See also the paper by Professor Lapworth, on "The Secret of the Highlands," *Geol. Mag.* 1883; and *postea*, pp. 792, 882.

the structure of the Alps.[1] As far back as the year 1883 he traced a series of gigantic displacements from the line of the Lake of Lucerne into the Tyrol. One of these, which he has since worked out in much detail, runs from the Uri-Rothstock eastwards through the cantons Uri and Glarus, winding in vast curves of outcrop from the valley of the Linth to that of the Rhine. This line of stupendous overthrust passes through the Glärnisch and its so-called "double-fold." The structure of the district in his view is given in Fig. 382, which passes through the same ground as that shown in Heim's

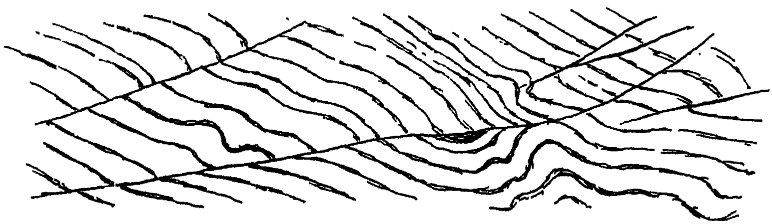


Fig. 281.—Thrust-planes in Jurassic Limestones, Lauterbrunnen, Switzerland.

section (Fig. 257). Having had the advantage of traversing some of the thrust-planes in this region, I have convinced myself that, while there has been undoubtedly much folding, the main structure is correctly given by Rothpletz.

Similar observations have been made in Scandinavia, where a series of gigantic overthrusts of the Archæan and crystalline schists upon the older Palæozoic formations has been followed along the axis of the country for a distance of some 800 kilometres or 500 English miles, but it may be continuous for as much as 1800 kilometres (1118 miles). The thrusts are gently inclined or undulating planes, and the horizontal displacement of the largest of them is estimated by Törnebohm at as much as 130 kilometres or 80 miles.

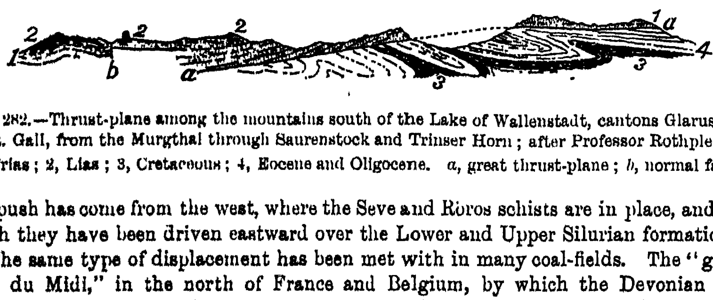



Fig. 282.—Thrust-plane among the mountains south of the Lake of Wallenstadt, cantons Glarus and St. Gall, from the Murgthal through Saurenstock and Trinser Horn; after Professor Rothpletz.
1, Trias; 2, Lias; 3, Cretaceous; 4, Eocene and Oligocene. *a*, great thrust-plane; *b*, normal fault.

The push has come from the west, where the Seve and Röros schists are in place, and from which they have been driven eastward over the Lower and Upper Silurian formations.[2]

The same type of displacement has been met with in many coal-fields. The "grande faille du Midi," in the north of France and Belgium, by which the Devonian rocks have been pushed over the Carboniferous, is a well-known and remarkable example of it. Professor Kayser has recently mapped and described a series of large flat overthrusts to the east of the Dill, between Ehringshausen and Hohensolms, by which successive slices of the Middle Devonian formations have been pushed over the Upper

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[1] See his papers cited on p. 677. Overthrusts in the Swiss Jura are noted in the 'Livret Guide' of the Congrès Géol. Internat. Zurich, 1894.

[2] See the large and important memoir by this geologist, "Grundragen af det Centrala Skandinaviens Bergbyggend," *K. Vet. Akad. Stockholm Handling*, xxviii. No. 5 (1896), pp. 212. This remarkable structure has been shown on a sketch-map of Sweden on a scale of 1 : 1,500,000, published in 1901 by the Sveriges Geologiska Undersökning under the direction of Mr. Törnebohm. See also an interesting paper with map by Holmquist in *Geol. Fören. Stockholm*, xxiii. p. 55; and *postea*, pp. 796, 898.

members and both over the Culm, while a system of later normal faults has cut and shifted these thrust-planes, as in N.W. Scotland.[1] It will be remembered that the same structure is conspicuously displayed at the lower ends of the glaciers of North Greenland and Spitzbergen (*ante*, p. 547).

**Throw of Faults.**—That normal faults are vertical displacements of parts of the earth's crust is most clearly shown when they traverse stratified rocks, for the regular lines of bedding and the originally flat position of these rocks afford a measure of the disturbance. In Fig. 278, the same series of strata occurs, on either side of each of the two faults, so that measurement of the amount of displacement is here obviously simple. The measurement is made from the truncated end of any given stratum vertically to the level of the opposite end of the same stratum on the other side of the fault. Where the fault is vertical, like that to the right in Fig. 278, the mere distance of the fractured ends from each other is the amount of displacement. In the case of an inclined fault, the level of the selected stratum is protracted across the fissure until a vertical from it will reach the level of the same bed, as shown by the dotted lines. The length of this vertical is the amount of vertical displacement, or the *Throw* of the fault. The throw of faults varies from less than an inch to several thousand feet.

Unless beds, the horizons of which are known, can be recognised on both sides of a fault, exposed in a cliff or other section, the fault at that particular place does not reveal the extent of its displacement. It would not, in such a case, be safe to pronounce the fault to be large or small in the amount of its throw, unless we had other evidence from which to infer the geological horizon of the beds on either side. A fault with a considerable amount of displacement may make little show on a cliff; while, on the other hand, one which, to judge from the jumbled and fractured ends of the beds on either side, might be supposed to be a powerful dislocation, may be found to be of comparatively slight importance. Thus, on the cliff near Stonehaven, in Kincardineshire, one of the most notable faults in Great Britain runs out to sea, between the ancient crystalline rocks of the Highlands and the Old Red Sandstones and conglomerates of the Lowlands of Scotland. So powerful have been its effects that the strata on the Lowland side have been thrown on end for a distance of two miles back from the line of fracture, so as to stand upright along the coast-cliffs like books on a library shelf. Yet at the actual point where the fault reaches the sea and is cut in section by the shore-cliff, it is not revealed by a band of shattered rock. On the contrary, no one would at first be likely to suspect the existence of a fault at all. The red sandstone and the reddened Highland schists have been so compressed and, as it were, welded into each other, that some care is required to trace the demarcation between them.

**Dip-Faults and Strike-Faults.**—The same fault may give rise to very different effects, according to variations in the inclination or curvature of the rocks which it traverses, or to the influence of branch faults diverging from it. Faults among inclined strata may, in most districts,

[1] E. Kayser, *Jahrb. K. Preuss. Geol. Landesanst.* 1900, p. 7.

be conveniently grouped into two series, one running in the same general direction as the dip of the strata, the other approximating to the trend of the strike. They are accordingly classified as *dip-faults* and *strike-faults*, which, however, are not always to be sharply marked off from each other, for the dip-faults will often be observed to deviate considerably from the normal direction of dip, and the strike-faults from the prevalent strike, so as to pass into each other.

A dip-fault produces at the surface the effect of a lateral shift of the strata. This effect increases in proportion as the angle of dip lessens, but ceases altogether when the beds are vertical. Fig. 283 may be taken as a plan of a dip-fault (*f f*) traversing a series of strata which dip northward at 20°. The beds on the east side look as if they had been pushed horizontally southwards. That this apparent horizontal displacement is due really to a vertical movement, and to the subsequent planing down of the surface by denuding agents, will be clear, if we consider what must be the effect of the vertical ascent or descent of the inclined beds at a dislocation. The part on one side of the fracture may be pushed up, or, what is equivalent, that on the other side may be let down. If the strike of the beds be supposed to be east and west, then a horizontal plane cutting the dislocated strata will show the portion on the west or upthrow side of the fault lying to the north of that on the east or downthrow side. The effect of denudation has usually been practically to produce such a plane, and thus to exhibit an apparently lateral shift. This surface displacement has been termed the *heave* of a fault. Its dependence upon the angle of dip of the strata may be seen by a comparison of Sections A and B in Fig. 284. In the former, the bed *a b*, which may be supposed to be one of those in Fig. 283, dipping north at 20°, once

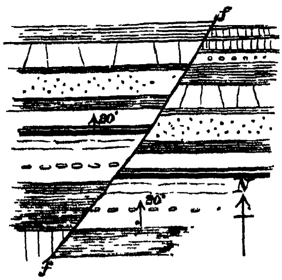

Fig. 283.—Plan of Strata cut by a Dip-Fault.

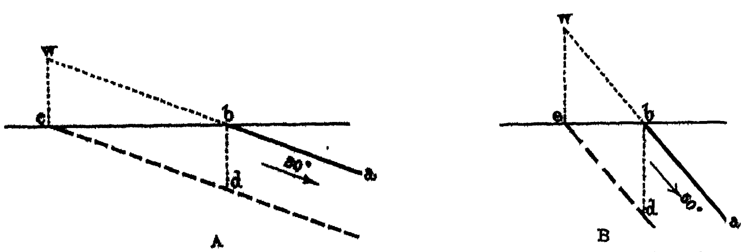

Fig. 284.—Sections to show the variation of horizontal displacement or Heave of Faults, according to the angle of inclination of strata.

prolonged above the present surface (marked by the horizontal line), is represented as having dropped from *w b* to *e d*. The heave amounts to the horizontal distance between *e* and *b*, the throw being the vertical distance between *b* and *d*. But if the angle should rise to 50°, as in B,

though the amount of throw or vertical displacement is there one-fourth greater, the heave or horizontal shift diminishes to less than a half of what it is in A. This diminution augments with increase of inclination till among vertical beds there is no heave at all, though a fault with a horizontal thrust will cause a lateral shift even in vertical strata (see Fig. 366).

Strike-faults, where they exactly coincide with the strike, may remove the outcrops of some strata by never allowing them to reach the surface. Fig. 285 shows a plan (A) and section (B) of one of these faults, *f f*,

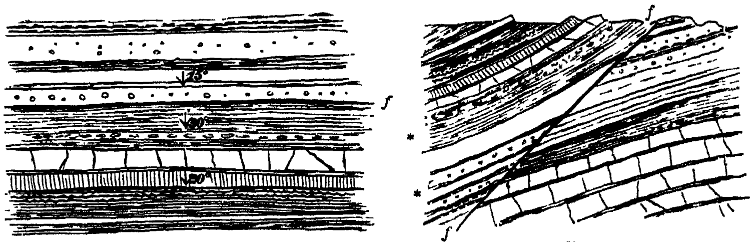


Fig. 285.—Strike-Fault.
A, plan; B, section across the plan in the line of the arrows.

having a downthrow towards the direction of dip. In crossing the strike, we pass successively over the edges of all the beds, except the part between the asterisks, which is cut out by the fault as shown in the section. It seldom happens, however, that such strict coincidence between faults and strike continues for more than a short distance. The direction of dip is apt to vary a little even among comparatively undisturbed strata, every such variation causing the strike to undulate, and thus to be cut more or less obliquely by the line of dislocation, which may nevertheless run quite straight. Moreover, an increase or diminution in the throw of a strike-fault will have the effect of bringing the dislocated ends of the beds against the line of dislocation. In Fig. 286, for instance, which

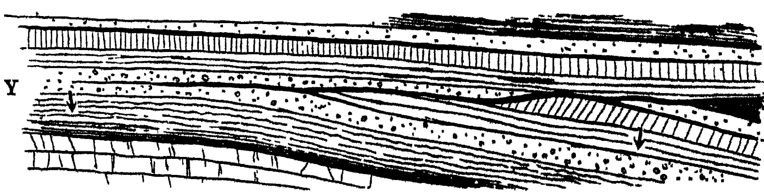


Fig. 286.—Plan of Strata traversed by a diminishing Strike-Fault.

represents in plan another strike-fault (*f*), we see that the amount of throw increases towards the right so as to allow lower beds successively to appear on one side, while towards the left it diminishes, and finally dies out in bed Y.

Their effects become more complicated where faults traverse undulating and contorted strata. The connection between folding and fracture

has already been adverted to in the case of monoclinal bends. It sometimes happens that the plications are subsequently fractured, so that the fault may appear to be alternately a downthrow on opposite sides, according to the position of the arches and troughs which it crosses. This structure may be illustrated by a plan and sections of a dislocated

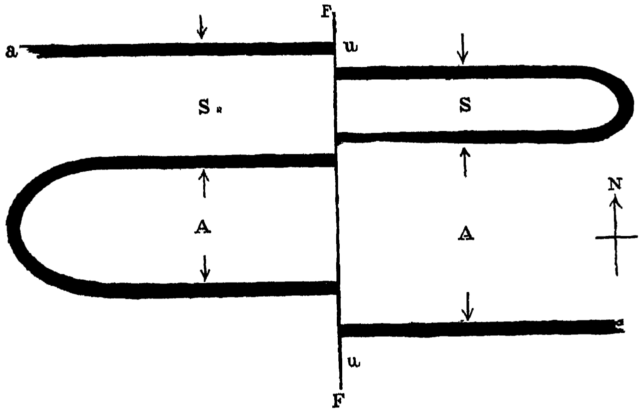


Fig. 287.—Plan of Anticline (A) and Syncline (S), dislocated by a Fault (F F).

anticline and syncline, which will also show clearly how the apparently lateral displacement of outcrop produced by dip-faults is due to vertical movement. Fig. 287 represents a plan of strata thrown into an anticlinal fold AA and a synclinal fold SS, and traversed by a fault FF, having an upthrow (*u u*) to the east. A dip-fault shifts the outcrop

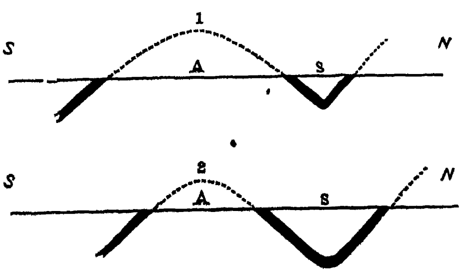


Fig. 288.—Sections along the Fault in Fig. 287.
1, section along the upcast side; 2, section along the downthrow side

towards the dip on the upthrow side, and this will be observed to be the case here. On the west side of the fault, the black bed *a*, dipping towards the south, is truncated by the fault at *u*, and the portion on the upthrow side is shifted forwards or southward. Crossing the syncline, we meet with the same bed rising with a contrary dip; and as the upthrow of the fault still continues on the same side, the portion of the bed on the west side of the fault must be sought farther south. The effect of the fault on the syncline is to widen the distance between the two opposite

outcrops of a bed on the downthrow side, or to narrow it on the upthrow side. On the southern slope of the anticline A, the same bed once more appears, and again is shifted forwards, as before, on the upthrow side. Hence in an anticline, the reverse effect takes place, for there the space between the two outcrops is narrowed on the downthrow side. A section along the east or upcast side of the fault would give the structure represented in Fig. 288 (1); while one along the downcast side would be as in (2). These two sections illustrate how the shifting of the outcrops at the surface can be simply explained by a mere vertical movement.

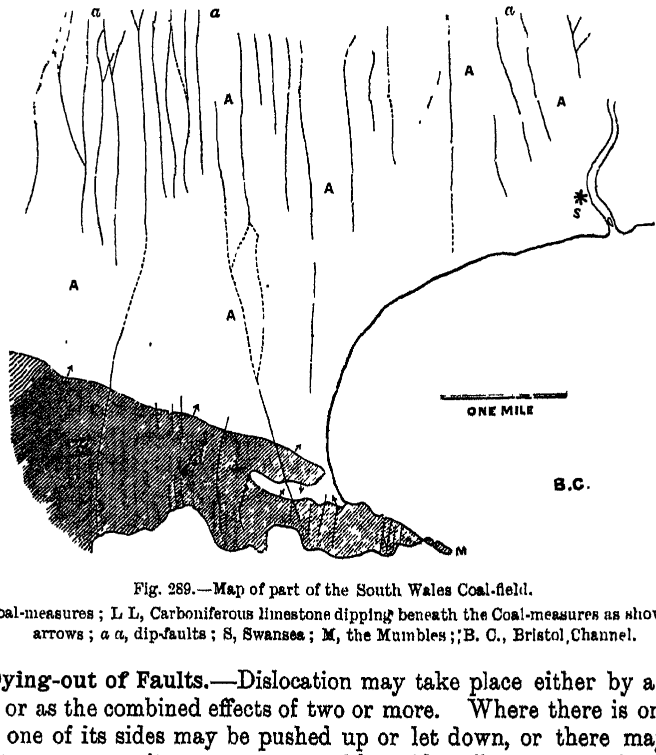


Fig. 289.—Map of part of the South Wales Coal-field.
A A, Coal-measures ; L L, Carboniferous limestone dipping beneath the Coal-measures as shown by the arrows ; *a a*, dip-faults ; S, Swansea ; M, the Mumbles ; B. C., Bristol Channel.

**Dying-out of Faults.**—Dislocation may take place either by a single fault, or as the combined effects of two or more. Where there is only one fault, one of its sides may be pushed up or let down, or there may be a simultaneous opposite movement on either side. In any case, there must be a gradual dying-out of the dislocation towards either end ; and one or more points where the displacement has reached a maximum. Sometimes, as may be seen in coal-workings, a fault, with a considerable maximum throw, splits into minor faults at the terminations. In other cases, the offshoots take place along the line of the main fissure. Exceedingly complicated examples occur in some coal-fields, where the connected faults become so numerous that no one of them deserves to be called the main or leading dislocation. By a series of branch-faults, the effect of a main fault may be neutralised or reversed. Suppose, for example, that a main fault at its eastern portion throws down 60 fathoms to the north,

and that at intervals three faults on the same side strike off from it, each having a downthrow of 25 fathoms to the east; the combined effect of these branch faults will be to reverse the throw of the main fault towards its western end, and produce a downthrow of 15 fathoms to the south.

**Groups of Faults.**—The subsidence or elevation of a large mass or block of rock has usually taken place by a combination of faults. Detailed maps of coal-fields, such as those published by the Geological Survey of

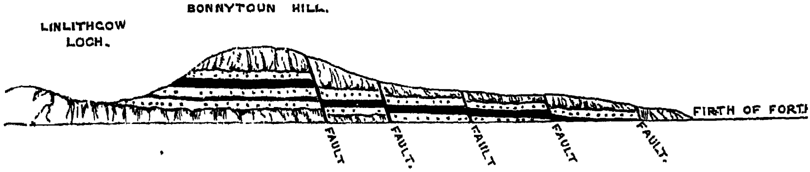


Fig. 290.—Step-Faults, Linlithgowshire.

Great Britain on a scale of six inches to a mile, furnish much instructive material for the study of the way in which the crust of the earth has been reticulated by faults. In most cases, dip-faults are predominant, sometimes to a remarkable extent, as in the portion of the South Wales coal-field represented in Fig. 289. In other places, the dislocations run in all directions, so as to divide the ground into an irregular network.

It often happens that, by a succession of parallel and adjoining faults, a series of strata is so dislocated that a given stratum, which may be near the surface on one side, is carried down by a series of steps to some distance below. Excellent examples of these Step-faults (Fig. 290) are to

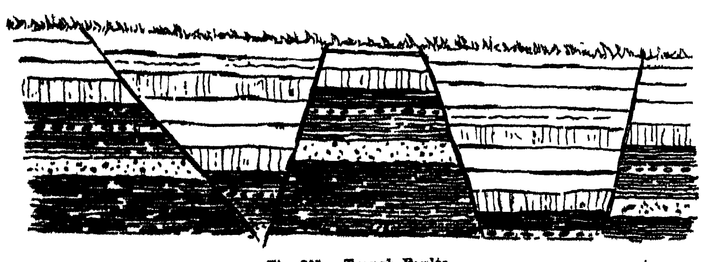

Fig. 291.—Trough-Faults.

be seen in the coal-fields on both sides of the upper part of the estuary of the Forth. Instead, however, of having the same downthrow, parallel faults frequently show a movement in opposite directions. If the mass of rock between them has subsided relatively to the surrounding ground, they are Trough-faults (Fig. 291), and enclose wedge-shaped masses of rock. It will be observed that the hade of these faults is in each case towards the downthrow side, and that the wedge-shaped masses with broad bottoms have risen, while those with narrow bottoms and broad tops have sunk.

The faults of a district may not have been the result of one series of

movements, but of a long succession of displacements, or of renewed disturbance after prolonged quiescence. One fault sometimes displaces another. In regions of reversed faults and thrust-planes, as has been pointed out above, normal faults have sometimes taken place long after the first dislocations.

**Detection and tracing of Faults.**—As a rule, faults give rise to little or no feature at the surface, so that their existence would commonly not be suspected. In some places, where a fault has brought together two groups of rock of unequal durability, the harder mass will usually be found to rise above the softer, and may form a long band of higher ground, the margin of which is defined by the line of dislocation. Occasionally the broken rocks along a fault have been removed by denudation, leaving a long line of hollow or even a more marked gash. The most stupendous display of a line of dislocation at the surface of the earth is probably that of the great rift which runs through the centre of East Africa from Abyssinia for some 1500 miles southward to beyond the southern end of Lake Nyassa.

Faults comparatively rarely appear in visible sections, but are apt rather to conceal themselves under surface accumulations just at those points in a ravine or other natural section where we might hope to catch them. Yet they undoubtedly constitute one of the most important features in the geological structure of a district or country, and should consequently be traced with the greatest care. In the majority of cases, in countries like much of Central and Northern Europe, where the ground is covered with superficial deposits, the position of faults cannot be seen, but must be inferred; though it must be admitted that geologists have been prone to great recklessness in this respect, introducing faults for which there was little or no actual evidence, but which were convenient for the explanation of theoretical views of the structure of a district. Experience will teach the student that the mere visible section of a fault, on some cliff or shore, does not necessarily afford such clear evidence of its nature and effects as may be obtained from other parts of the region, where it does not show itself at the surface at all. In fact, he might be deceived by a single section with a fault exposed in it, and might be led to regard that fault as an important and dominant one, while it might be only a secondary dislocation in the near neighbourhood of a great fracture, for which the evidence would be elsewhere obtainable, but which might never be seen itself. The actual position (within a few yards) of a large fault, its line across the country, its effect on the surface, its influence on geological structure, its amount of vertical displacement at different parts of its course—all this information may be admirably worked out, and yet the actual fracture may never be seen in any one single section on the ground. A visible exposure of the fracture would be interesting: it would give the exact position of the line at that particular place; but it would not be necessary to prove the existence of the fault, nor would it perhaps furnish any additional information of importance. The existence of an unseen fault may usually be determined by an examination of the geological structure of a district. An abruptly truncated outcrop is

always suggestive of fracture, though sometimes it may be due to unconformable deposition against a steep declivity. If a series of strata be discovered, in a water-course or other exposure, dipping continuously in one general direction at angles of 10° or more, and if, at a short distance, another portion of the same series be found inclined in another direction, the two thus striking at each other, a fault will almost always be required to explain their relation. If all the evidence obtainable, from the sections in water-courses or otherwise, be put upon a map (as in A, Fig. 292), it will be seen that a dislocation must run somewhere near the points marked

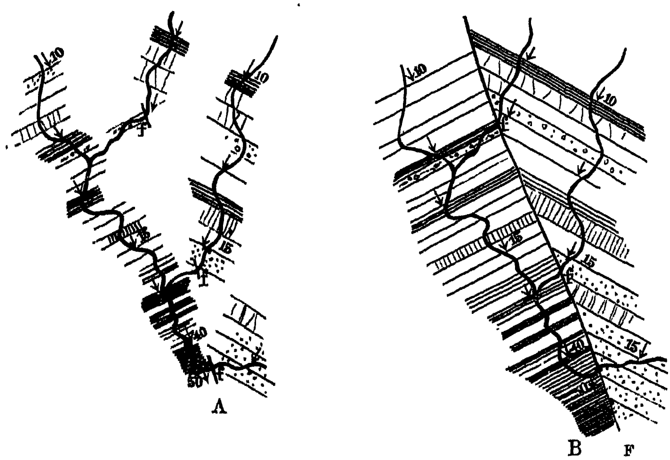


Fig. 292.—Map, illustrating the detection of an unseen Fault.
A, field-map, showing the data actually obtained on the ground; B, completed map, showing the geological structure of the district.

*f f*, as there is no room for either series to turn round so as to dip below the other. They must be mutually truncated. The completed map would represent them separated by a fault (F, in B). The upthrow or downcast side of the dislocation would be determined by the observer's knowledge of the order of superposition of the respective groups of strata.[1]

The existence of a fault having been thus proved from an examination of the geological structure of the ground, its line across the country may be approximately laid down—1st, by getting exposures of the two sets of rock, or the two ends of a severed outcrop on either side, as near as possible to each other, and tracing the trend of the dislocation between; 2nd, by noting lines of springs along the supposed course of the fault, subterranean water frequently finding its way to the surface along fault-fissures; 3rd, by attending to surface features, such as lines of hollow, or of ridge rising above hollow, the effect of a fault often being to bring rocks of unequal resistance together, so as to allow the more durable to rise more or less steeply from the fracture.[2]

[1] On a method of determining the actual direction of movement, whether lateral or vertical, in faults, see P. Lake, *Geol. Mag.* 1897, p. 545.

[2] De la Beche, 'Geol. Observer,' p. 561.

**Origin of Faults.**—In countries where the rocks have not undergone much disturbance, and where therefore stratified formations are still not far removed from their original approximate horizontality, faults are generally due to mere subsidence of the crust (Normal Faults). As has been above stated, the great majority of faults everywhere belong to this class. Van Hise has proposed to class them as *Gravity Faults*, seeing that gravity is chiefly concerned in their introduction. Where, on the other hand, rocks have been much compressed and plicated, both minute and also gigantic faults have been produced by tangential thrust (Reversed Faults, Overthrust). Experimental illustration has shown how by lateral pressure on suitable materials most of the chief features in these faults can be imitated. In the case of normal faults, a part of the crust of the earth is widened until this effect leads to the plication of the subsiding area, which thus adjusts itself to its new position. In the case of overthrusts, the area of the crust is diminished. Both lateral thrust and subsidence have often been concerned in the origin of the dislocations of a much-fractured area.

END OF VOL. I

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